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ORIGIN & FATE OF THE UNIVERSE

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Measuring the universe

BY STEVE NADIS

A quest to understand our cosmic origin and figure out where we come from has engaged humans for thousands of years. During most of that time, this venture was strictly an intellectual exercise — stargazers and philosophers trying to fathom our place within the enormousness of the heavens. But cosmology has recently crossed a threshold, moving into the realm of a hard and testable science, where observers can verify the predictions of theorists. This special issue contains the best articles on cosmology from recent years of *Astronomy,* updated to reflect new discoveries.

Cosmology's shift has come about through advances in technology. Armed with new precision tools, astronomers seek to chart the history of the universe and determine its size, shape, structure, and composition.

Leading the charge has been a satellite orbiting Earth since July 2001, the Wilkinson Microwave Anisotropy Probe (WMAP). Its instruments can discern a one-millionth of a degree temperature difference in the cosmic microwave background. This let the WMAP team calculate the age of the universe as 13.7 billion years, accurate to within 1 percent. The team also found that the first stars appeared earlier than expected, just 200 million years after the Big Bang.

The universe according to WMAP contains 4 percent ordinary matter and just 0.4 percent luminous matter — stars, galaxies, and the like. All the rest consists of dark matter (23 percent) and dark energy (73 percent).

These results are a triumph — but they also reveal a sobering fact: 96 percent of everything is almost a total mystery because we can't yet describe the true nature of dark matter and dark energy.

Here lies a great paradox. While extolling the virtues of precision cosmology, astronomers find themselves in an embarrassing position: They don't know what most of the universe is made of. They don't know what caused the Big Bang. They can't explain how inflation works, nor identify the energy that drives it. And they can't even say where familiar, everyday matter comes from.

And those are just things we *know* we don't understand well enough! What about the things we can't even claim ignorance of? Ten years ago, few astronomers would have believed that three-fourths of the universe's total energy lies in a mysterious form that we can say little about beyond labeling it "dark." Other surprises, perhaps equally great, may lurk around the corner.

Do all these mysteries shake the confidence of cosmologists? Max Tegmark of the University of Pennsylvania says it's not time to push the panic button just yet. When evidence about the overwhelming dominance of dark matter and dark energy started coming in, he notes, "The first reaction for many of us was denial: 'It can't be that weird.' Now we have to admit that it *is* that weird."

Yet he finds something positive in all this. For the first time, he says, "we have the tools to start measuring the properties of dark matter and dark energy — and, perhaps, narrow the number of models."

However successful cosmology is, notes University of Chicago theorist Sean Carroll, many deep mysteries will remain, and the answers to them will undoubtedly lead to the next level of puzzles. "It's a good bet," Carroll says, "that the fun is only beginning."

Welcome to cosmology!

ORIGIN & FATE OF THE UNIVERSE

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Absurd universe

The visible matter of the universe — the part we can actually see — is a surprisingly small piece of the whole. /// BY MICHAEL S. TURNER

Place $1 worth of pennies in a pile. Select only four pennies, preferably nice, shiny ones, and set them apart. Cover the pile of 96 pennies with a cloth. What you've created is a crude model of the universe, where what we see with our eyes is only a small part of what our brain knows to exist.

Sound absurd? On February 11, 2003, the first results from the Wilkinson Microwave Anisotropy Probe (WMAP), an orbiting observatory, showed us just how much we can't see. WMAP, conceived in 1995 and launched in June 2001, was a follow-up to NASA's Cosmic Microwave Background Explorer (COBE), which, in 1992, discovered tiny (0.001 percent) variations in the intensity of cosmic microwave radiation across the sky. These variations provided a map of sorts to what the universe was like some 400,000 years after its beginning. Using this map as a starting point, astronomers predicted the makeup of the universe. What they needed, however, was a better instrument to confirm the prediction.

WMAP unveiled — with remarkable resolution — a shadowy universe comprised of 4 percent visible matter (stars, dust, and gas), roughly 23 percent dark matter that holds the universe together, and roughly 73 percent mysterious dark energy that is accelerating the expansion of the universe.

Scientists have a theory to go along with this picture: The tiny patterns in the millionth-of-a-degree temperature fluctuations were the seeds of what later became galaxy clusters and other large-scale structures we observe today.

Early ideas

A few decades ago, the idea that the visible universe made up only 4 percent of all there is would have sounded absurd to most astronomers. Hints of our universe's strangeness, however, were found more than seventy years ago. Fritz Zwicky, the eccentric Swiss-American astronomer based at Caltech, pointed out in the 1930s that the individual

Updated from the November 2003 issue of *Astronomy*

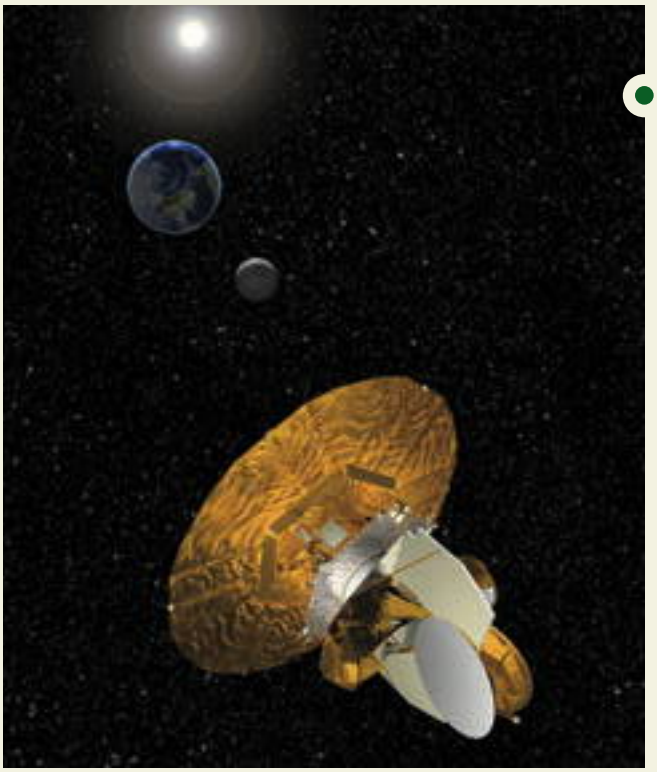
ILLUSTRATING OUR ABSURD UNIVERSE is not an easy task. Figuring out the percentages is relatively easy. The problem comes from the fact that two of the three "ingredients" that comprise the universe are invisible. Until we find a way to print invisible images, aquarium gravel will have to do. WILLIAM ZUBACK

4% of the universe is made of baryonic matter, a term referring to the fact that visible matter is composed of baryons, groups of quarks subject to the strong nuclear force.

23% of the universe is made of material that astronomers call dark matter. Dark matter is similar to baryonic matter because it has mass, and therefore exerts gravitational force.

73% of the universe seems to be an unknown type of energy that astronomers call dark energy, some kind of antigravitational force that is accelerating the expansion of the universe.

/// WMAP CLOSE-UP

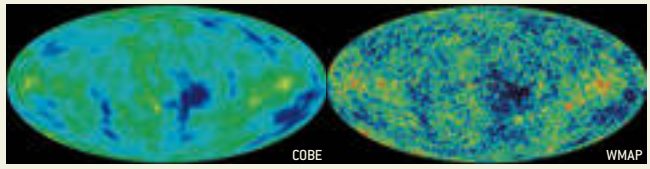


NASA/WMAP SCIENCE TEAM

WMAP floats lazily in space in this artist's depiction (left). Launched on June 30, 2001, WMAP maintains a distant orbit at the second Lagrangian Point, or "L2," four times farther than the Moon and approximately a million miles from Earth.

Compare the images from WMAP (below right) and COBE (below left). Each image shows an all-sky picture of the universe when it was very young, only 380,000 years after the Big Bang. In 1992, NASA's COBE mission first detected tiny temperature fluctuations in the cosmic microwave background radiation (depicted in the figure as color variations). This was a landmark discovery. Notice the much higher resolution of the 2003 WMAP image. Because of advances in technology, the WMAP image brings the microwave sky into sharper focus.

WMAP allowed astronomers to observe the first light to break free in the infant universe, the afterglow of the Big Bang. Patterns imprinted on this light reflect the conditions set in motion a tiny fraction of a second after the Big Bang. The image (below right), the first detailed, all-sky picture taken by WMAP, reveals temperature fluctuations (shown as color differences) more than 13 billion years old that correspond to the "seeds" that grew into galaxies. — *Michael E. Bakich*



members of the Coma cluster of galaxies were moving too fast to be bound by the gravitational effects of their stars alone. Without the additional gravity of some unseen form of "dark" matter — perhaps even in the form of billions of small bodies like Jupiter — the galaxies within the Coma cluster would have long since dispersed. Today, astronomers can map the amount of dark matter contained in many galaxy clusters by studying how those clusters bend light from more distant objects.

Clusters were strange, and Zwicky even more — so it was easy to ignore the dark matter problem. However, a complication arose from another direction. In 1964, Bell Lab scientists Arno Penzias and Robert Wilson discovered the cosmic microwave background (CMB) radiation. The Big Bang theory predicts that the early universe was a very hot place. As it expanded, however, the radiation within it expanded into a larger and larger space and cooled. Today the universe is filled with the Big Bang's remnant heat — the CMB. The CMB contributes only negligibly to the energy content of the universe, about 0.01 percent of the total, but it provides an exquisite record of the universe at a simpler time.

Because the universe is expanding, its radiation is becoming weaker as photons fill an ever-larger space and as each photon's energy is redshifted. Looking forward, this means the energy of the CMB will become less important; but looking backward, it means that earlier than 10,000 years after the Big Bang, the radiant energy of the CMB was very important. In the early universe, matter was the bit player.

Michael S. Turner *is chairman of the Department of Astronomy and Astrophysics at the University of Chicago.*

Dark proof

Vera Rubin, an astronomer at the Carnegie Institution, and others brought the dark matter problem much closer to home in the 1970s and 1980s. With the discovery that both stars and clouds of gas farthest from the center of the galaxy are moving too fast to be held by the gravity of just stars, Rubin and her colleagues showed how dark matter actually holds galaxies like our own together. Even at our position in the Milky Way, about half the gravity that keeps us in orbit is due to unseen dark matter.

The late David Schramm explained how the production of the lightest elements, especially deuterium, in the Big Bang could be used to measure the total amount of ordinary matter. The conclusion was shocking — no matter what form it was in, there simply was not enough ordinary matter (and thus gravity) to hold the universe together. WMAP, because of its exquisite precision, found a clue to this puzzle in the cosmic microwave background radiation. Carl Sagan was right when he said we are made of star stuff, but cosmologists now know that the universe is not.

Dark candidates

The infusion of particle physics into cosmology in the 1980s brought a revolutionary idea: Dark matter may exist as particles of a new form of matter. Three particle suspects have emerged: the neutrino (actually known to exist), the neutralino (100 times heavier than a proton), and the axion (one-trillionth the mass of an electron). For now, the neutralino and axion exist only in the minds of particle theorists and cosmologists.

The particle dark matter idea got a boost in 1998. The Super-Kamiokande detector in Japan, studying neutrinos produced in

A theoretical lensing galaxy (top right) produces more than one image of an object because the galaxy's gravity bends the object's light around the galaxy in several directions. This effect — the gravitational bending of light — was first predicted by Einstein and explained in his general theory of relativity.

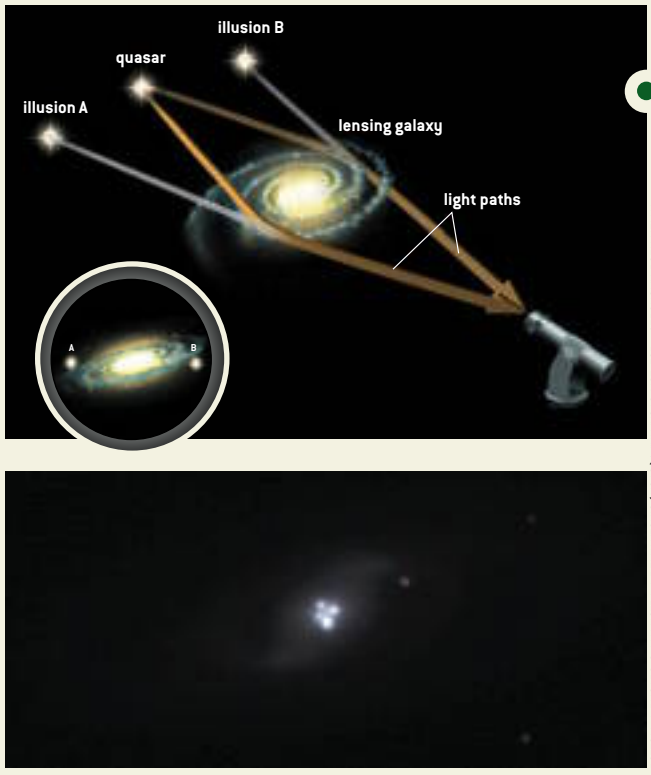
In the 1930s, astronomer Fritz Zwicky put forth the idea that galaxy clusters must contain some form of dark matter. Otherwise, the motions of individual galaxies within the clusters would send them hurling through space. Because the amount of lensing by galaxy clusters is due to the amount of visible matter plus the amount of dark matter, astronomers can calculate the amount of dark matter galaxy clusters contain.

Lying in the constellation Pegasus the Winged Horse, Einstein's Cross (bottom right) provides an excellent example of gravitational lensing. The single quasar, designated Q2237+0305, shows up as four images because of the lensing spiral galaxy between the quasar and Earth. This image was taken by the 3.5-meter WIYN (Wisconsin, Indiana, Yale, NOAO) telescope, on October 4, 1999.

This system also is known as Huchra's Lens, after its discoverer, but more popularly as Einstein's Cross. Einstein postulated this effect as soon as he realized that gravity can bend light and produce lens-like effects.

The distance to this lensing galaxy is 400 million light-years, which may sound like an immense stretch until you compare it to the quasar behind the galaxy, Q2237+0305, which is 8 billion light-years away, twenty times the distance of the lensing galaxy.

Other examples of this phenomenon exist and have been imaged with instruments such as the Hubble Space Telescope. — *Michael E. Bakich*



BOTTOM: J. RHOADS, S. MALHOTRA, I. DELLANTONIO (NOAO)/WIYN/NOAO/NSF; TOP: *ASTRONOMY*, ROEN KELLY

Earth's atmosphere by cosmic rays and also in the interior of the Sun, showed that these particles have mass, albeit very little. Because so many neutrinos are left over from the Big Bang, if a single neutrino has even a tiny mass, all neutrinos combined become significant players in the cosmic mix. In the spring of 2002, astronomers at the Sudbury Neutrino Observatory in Ontario, Canada, studying neutrinos from the Sun, discovered more evidence that neutrinos have mass. And in the autumn of 2003, two experiments in Japan using human-made neutrinos further strengthened the case that neutrinos contribute less than 0.3 percent of the total matter of the universe.

The story is not over yet. Neutrinos cannot account for all the dark matter; they appear to be just a cosmic spice. Particle physicists and cosmologists are pinning their hopes on the neutralino and axion, both referred to as cold dark matter. (This name comes from the assumption that dark matter particles were moving slowly when galaxies began to form.) Scientists are trying to produce neutralinos using particle accelerators. They also are trying to detect axions and neutralinos with ultra-sensitive instruments to see if these hypothetical entities do, indeed, exist.

Dark energy

Just as many cosmologists and astrophysicists were getting used to the idea of particle dark matter and the fact that we are not made of the primary stuff of the universe, along came dark energy. Two groups of astronomers in the late 1990s, one led by Saul Perlmutter of Lawrence Berkeley Lab in California, and the other by Brian Schmidt of Mt. Stromlo Observatory in Australia, used distant supernovae as standard candles to measure the slowing of the expansion of the universe. They found, however, that instead of slowing down, the expansion is speeding up — apparently due to the repulsive gravitational action of something that doesn't give off light. This "something" is referred to as dark energy because the way it reacts with the rest of the universe implies a form of energy. If the accelerated expansion continues for another 150 billion years, the sky will darken, with only a handful of galaxies remaining visible.

Where do we go from here?

So, here we are in our absurd universe. The Big Bang provided a hot beginning, and its radiant energy controlled the universe's first 10,000 years. Stars illuminated the heavens but contributed only 0.4 percent of the total mass. The recipe for our universe today is crazier than even Zwicky could have imagined: one-third dark matter, two-thirds dark energy, a pinch of microwave energy, and at least three spatial dimensions. (String theorists insist there are many more unseen dimensions.) Dark matter breaks down into 4 percent dark, ordinary matter (the bulk of it in the form of gas that is still too hot to form stars), 30 percent elementary particles, and the rest, simply referred to as cold dark matter, is still to be identified.

The past two decades have brought major advances in understanding how the universe is put together. If we are truly in a golden age of cosmological discovery — and I believe we are — big new telescopes, space instruments, and accelerators will, over the next twenty years, help us make sense of this amazing universe in which we find ourselves. Although we can't expect to comprehend everything, the absurdity of our situation will at least become more apparent. A

Eight great mysteries

Startling discoveries of the past century have revealed much about our cosmic origin, but huge mysteries remain that will take astronomers years to decipher. /// BY MARK SINCELL

It's easy to forget that a century ago, no one had seen Pluto, and astronomers believed the universe was contained in the starry confines of the Milky Way Galaxy. This picture has become vastly more complex as we enter the 21st century.

Albert Einstein's theory of general relativity, which describes how gravity causes space-time to be curved, argues that every massive object puts a slight dent in the fabric of space-time, like a bowling ball on a mattress. Einstein, however, mistakenly believed the universe was unchanging. To keep it that way in his formulas, he postulated a new mathematical construct — the cosmological constant — to provide a repulsive force that would keep the universe from collapsing under the influence of its own gravity.

An obscure Russian mathematician, Alexander Friedmann, realized that Einstein's ideas about gravity could support an entirely different interpretation — the universe could be expanding rather than holding steady.

A Belgian cosmologist and Catholic priest, Georges Lemaître, also supported the expanding-universe hypothesis. In 1927, he argued that the well-known Doppler shift in light coming from "nebulae" (galaxies, in today's terms) toward longer, redder wavelengths — indicating the nebulae were moving away from Earth — showed that the universe is expanding. Lemaître theorized the universe started out very small and grew to fantastic proportions. Of course, Einstein didn't buy it.

However, in the 1920s, Edwin Hubble used the brightnesses of variable stars to establish a distance scale to the galaxies. Hubble found that the farther away a galaxy was from Earth, the faster it was moving away from us. We now believe the expansion is actually an expansion of space, not the motion of galaxies across space — a concept that Hubble never fully accepted.

In 1948, Ralph Alpher and George Gamow built upon Hubble's observations and Lemaître's idea and presented their theory of the Big Bang. The cosmic explosion, they claimed, would produce a primordial state of incredibly hot matter consisting of neutrons and their decay products. The then-outlandish idea also included a testable prediction that was ignored for years: The cool relic of the Big Bang would be detectable from Earth as microwave radiation.

In 1964 and 1965, AT&T Bell Laboratories scientists Arno Penzias and Robert Wilson used a radio telescope, which had been developed to

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THE STAR FORMING REGION S106 symbolizes the weird mysteries that litter the galaxy and the universe beyond. The story of cosmology, the origin and fate of the cosmos, is just now beginning to be understood in sufficient detail to put the major pieces of the story together. SUBARU TELESCOPE, NAOJ

listen to the first communication satellite, to detect a ubiquitous microwave hiss. The noise was independent of the direction in which they pointed the antenna. They recalibrated and cleaned the telescope, but the signal persisted. The radio static remained the same regardless of whether Penzias and Wilson pointed their telescope in the direction of the Sun or the Milky Way Galaxy, which suggested the radiation was neither solar nor galactic in origin.

Penzias and Wilson soon realized the static was the microwave radiation predicted by Alpher and Gamow. Suddenly, the Big Bang wasn't nearly so unthinkable after all. However, as with all great theories of the past centuries, and probably all great theories to come, the Big Bang raised more questions than it answered.

In 1998, independent teams of astronomers led by Brian Schmidt of the Mount Stromlo and Siding Spring Observatories in Weston Creek, Australia, and Saul Perlmutter at the Lawrence Berkeley National Laboratory in Berkeley, California, were recording the brightnesses of distant supernovae, ostensibly to measure the deceleration of the universe's expansion. Both teams found something every bit as unexpected as Penzias and Wilson's detection of the cosmic microwave background: The distant galaxies containing the supernovae aren't moving away from Earth at speeds that slow with time. Instead, the galaxies are accelerating away from us.

This discovery, as with major breakthroughs in the past, generated its own set of questions. The following mysteries recognize the tremendous accomplishments of the past century while acknowledging the still considerable work that lies ahead.

1 How multidimensional is the universe?

Except in magic shows, nobody actually pulls a rabbit out of an empty hat. For example, we live in a three-dimensional world, right? Perhaps not. Physicists have traditionally described the universe using four dimensions: the familiar three spatial dimensions and a time dimension. The model helped explain everything from the bending of starlight as it skirts the Sun to the formation of black holes. Now, physicists think they may have to add several more spatial dimensions.

COSMIC STRINGS, like these generated by a computer simulation, could reign in an 11-dimensional universe. C. B. ALLEN AND E. P. SHELLARD

Physicists are motivated by the "hierarchy problem." Simply put, they don't understand why gravity is vastly weaker than the other three fundamental forces of nature: the electromagnetic, strong, and weak forces. Physicists Lisa Randall of the Massachusetts Institute of Technology (MIT) in Cambridge, and Raman Sundrum of Johns Hopkins University in Baltimore, Maryland, recently proposed an explanation: add a dimension. In their model, we live in a four-dimensional world, but graviton particles, which carry the gravitational force, live in another. A small fifth-dimensional separation between the two worlds greatly diminishes the force of gravity.

String theorists go even further. They unify the four fundamental forces of physics in an 11-dimensional model in which tiny loops and bits of "string" are the most fundamental particles. But even the most optimistic string theorists doubt they will see these strings anytime soon. Theory predicts that the strings are one hundred million billion times smaller than the smallest subatomic particle created in the most powerful particle accelerators.

Evidence for the fifth dimension could arrive much sooner. Randall and Sundrum predict that the Large Hadron Collider in Geneva, Switzerland, which is due to begin operating in 2007, could generate enough energy to let a graviton briefly leak into our world.

2 How did the universe begin?

The consensus among cosmologists is that the visible universe erupted out of a singular event between 13 and 14 billion years ago. Within the first microsecond, the universe was an unimaginably hot soup of quarks and other exotic particles. As the soup cooled, quarks condensed into protons and neutrons and their cousins, hadrons and mesons. By the time the universe reached the ripe old age of 1 second, only neutrons, protons, photons, electrons, and neutrinos (three types of lightweight elementary particles and their antiparticle counterparts) remained. A series of nuclear reactions over the next 200 seconds created the nuclei of the three smallest elements.

Sound waves from the fading echo of the Big Bang rippled through the incredibly hot and dense fluid of the infant universe like ripples in a lake. Pulled by the positively charged protons, a dense swarm of negatively charged free electrons accompanied the ebb and flow of the soup. Collisions with these electrically charged species corralled and herded the photons along. When the universe reached its 380,000-year birthday, however, it had cooled enough for atoms to form. That set the photons free, and the universe was suddenly transparent. The liberated photons carried the fossil imprints of the early universe's density and temperature fluctuations as a pattern of brightness variations. Astronomers call this "relic radiation" — which was first observed by Penzias and Wilson — the cosmic microwave background (CMB).

When astronomers point microwave telescopes like the Cosmic Background Explorer or its successor, the Wilkinson Microwave Anisotropy Probe, in one direction and measure the temperature of the CMB, they observe radiation at 2.7° Celsius above absolute zero (or 2.7 kelvins). When they look in the opposite direction, they again get 2.7 K. There are some fluctuations, but they are tiny. The largest variation in the CMB is one part in 100,000.

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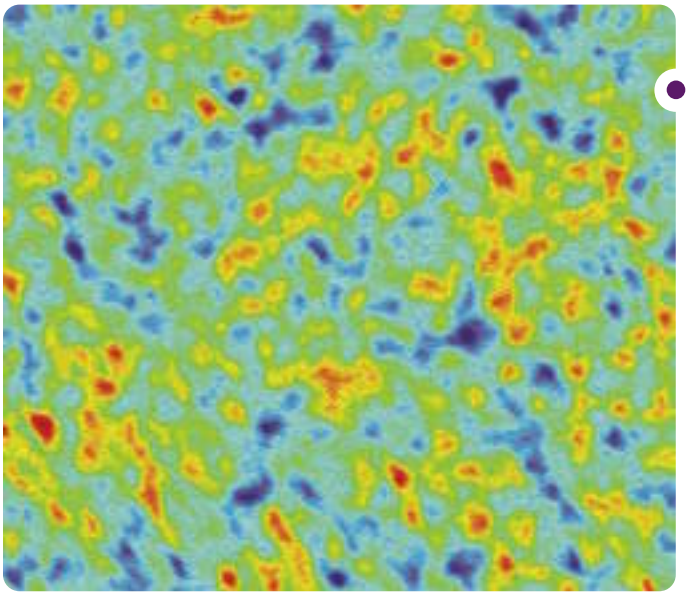


THE BIG BANG'S AFTERMATH contained tiny temperature variations that evolved into galaxy clusters and superclusters. THE BOOMERANG COLLABORATION

Cosmologists are intrigued by any explosion that could have generated such smoothness. It's as if every part of the early universe was connected. How could that be possible? While musing over this problem in the late 1970s, physicist Alan Guth, then at Stanford, had an astonishing realization: What if the visible universe started out as a tiny, extraordinarily uniform bubble that suddenly expanded so fast there was no time for it to change? Not only did Guth's inflation theory explain the one-part-in-100,000 smoothness of the CMB, but it also postulated that the lumpiness itself arose from quantum fluctuations occurring during inflation.

Cosmologists agree that, although the details are yet to be fully resolved, the tiny fluctuations in the early universe were amplified by gravity to form the large lumps astronomers see today — galaxies, clusters of galaxies, and other large-scale structures. And Guth's inflation theory even made a testable prediction: An inflated bubble universe would appear "flat" in cosmological terms. Flat means that parallel lines will never cross, even if they traverse the entire universe.

In recent years, astronomers have repeatedly tested the prediction of Guth, now at MIT, by measuring the angular sizes of the tiny variations in the CMB. Every time, they find that the universe is flat. "It is the dumbest, simplest solution to Einstein's equations that you could write down," says University of California, Berkeley astrophysicist Martin White. "But it happens to describe the universe very accurately."

As to what drove inflation, nobody knows. Physicists have suggested a long list of models to describe the inflating universe, but most of the proposed solutions are mathematical conveniences with no particular physical basis. "All the theories of inflation amount to proof that we don't have one good theory yet," says Fermi National Accelerator Laboratory astrophysicist Edward W. "Rocky" Kolb.

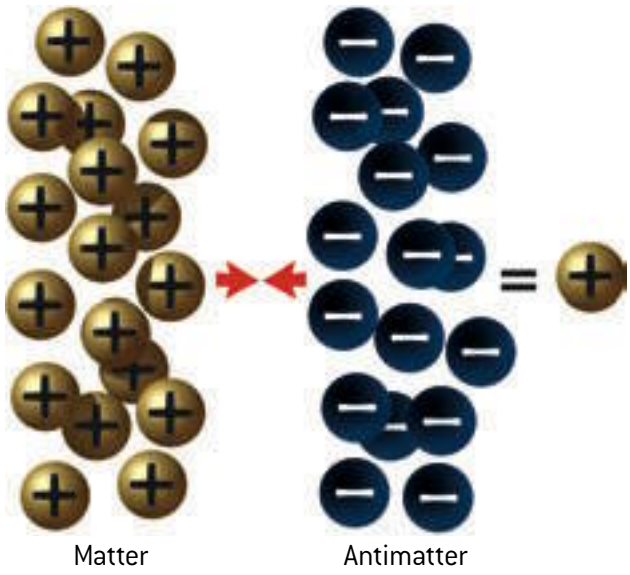
3 Why does matter fill the universe?

If the universe were exactly symmetrical, no planets, particles, or people would exist because it would have contained equal numbers of particles and antiparticles. And particles and antiparticles quickly annihilate, producing gamma rays. Such a universe would be full of radiation and no atoms; however, virtually no antimatter exists in the universe, which is hard for theorists to explain. Guth's inflation should have created equal amounts of matter and antimatter. (Of course, if matter and antimatter had formed in equal amounts and annihilated, there would be no theorists.) So how did matter survive annihilation?

It's possible the antimatter did survive but that it somehow resides in a distant part of the universe too far away to see. "It could be that there are anti-galaxies with anti-people somewhere else," notes University of California, Irvine physicist Jonathan Feng. "But that would have some strange consequences, which have not yet been seen."

A second possibility is that the universe is precisely symmetric, but it avoided the "annihilation catastrophe" after the Big Bang because the laws of physics have a slight preference for matter. This condition would have created a slight excess of matter, and the universe visible today is made of these leftovers.

In the mid-1960s, American particle physicists James Cronin and Val Fitch showed in their experiments that about 0.2 percent of the decay events of certain elementary particles violate the expected symmetry. Their colleagues were astonished. Cosmologists immediately argued the results might explain why the universe has matter, but the case is far from closed.



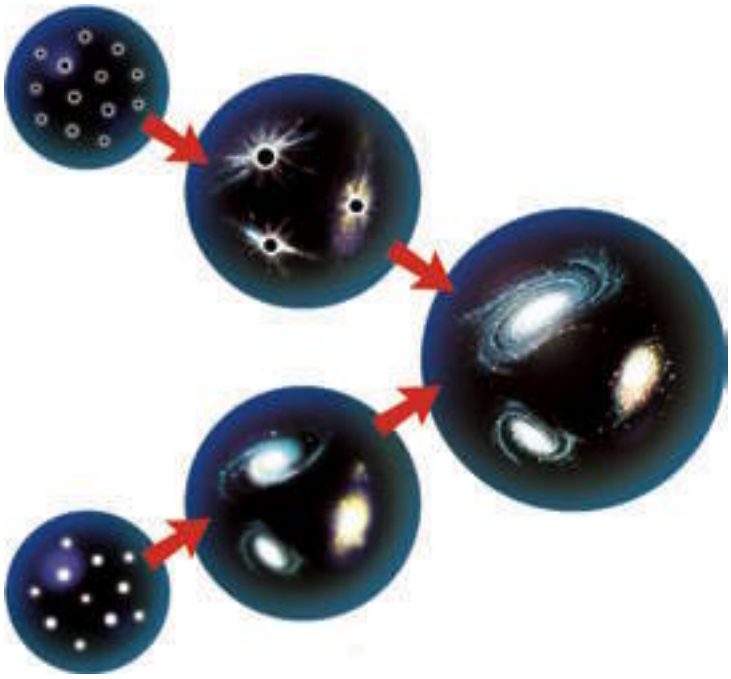
MATTER AND ANTIMATTER produced in the first moments of the universe would annihilate quickly, but the universe has a huge excess of matter and almost no antimatter today. *ASTRONOMY:* ROEN KELLY

4 How did galaxies form?

"We have a cartoon description of galaxy formation that makes a vague kind of sense," says White, "but it is not concrete." Where did the lumpiness in the infant universe come from, and how were the lumps later amplified by gravity into galaxies?

Cosmologists can't answer those questions, but they agree that clumps of matter scattered throughout the young universe collapsed under their own gravity, dragging protons and neutrons (collectively called baryons) along and heating them. The fast-moving baryons collided, lost energy, stuck together, and sank into gravitational "wells." Newborn galaxies strung themselves along the threads that define the surfaces of nearly empty, light-year-size voids.

Although three-dimensional galaxy maps generally confirm this bubble-bath model of the universe, the details are devilishly difficult



GALAXY-MAPPING SURVEYS may soon reveal which galaxy-formation model is correct. *ASTRONOMY:* ROEN KELLY

to understand. Do colliding spiral galaxies produce elliptical galaxies? If the answer is yes, then why do the chains of elliptical galaxies and spirals seem to trace out different patterns in the foam?

Progress on these questions has been slow, largely because it takes so long to measure galaxy distances, but it also has been steady. The Anglo-Australian 2dF Galaxy Redshift Survey collected more than 220,000 galaxy distances and the Sloan Digital Sky Survey (SDSS) team expects to create a 3-D map of a million galaxies when the survey winds down in 2005. So far, SDSS astronomers have measured the distances to more than 200,000 galaxies. "This data should really help us crack open the question of galaxy formation," says Ohio State University astrophysicist David Weinberg.

5 What is cold dark matter?

All the stars and galaxies in the sky amount to less than 0.5 percent of all the mass in the universe. And even if you add invisible clouds of atoms predicted to be floating in the distant universe, the total still comes to only about 4 percent. The rest is cold dark matter and dark energy. Although astronomers can't see dark matter directly, they believe it accounts for about 23 percent of matter in the universe because of the way it pulls on stars and bends light. Cold dark matter is congealed into filaments that thread the surfaces of cosmic voids hundreds to millions of light-years across. This shape suggests that dark matter is slow-moving, therefore cold. Fast-moving "hot dark matter" would have long ago smeared out the universe's mass, preventing galaxy formation. And cold dark matter particles must interact very weakly, if at all, with normal matter; otherwise, the spherical dark-matter halos that surround the Milky Way and other galaxies would have flattened into galaxy-like pancake shapes.

GALAXY CLUSTER Abell 2218 NASA/A. FRUCHTER/ERO TEAM

If cold dark matter particles would interact only with normal material, they would be easy to find. Actually, they may do just that, but too weakly to reveal themselves. It takes longer than the age of the universe for most of these particles to have their first collision.

Physicists are trying two approaches to increase their odds of bumping into one of the unobtrusive particles. One idea is to go big. Annihilations of dark-matter particles and their antiparticles in the center of the Milky Way or in the core of the Sun should create neutrinos. While neutrinos interact weakly with matter, one of these elementary particles should occasionally strike a water molecule, releasing a flash of light. In hopes of spotting one of these telltale flashes, physicists are converting the Mediterranean and Adriatic Seas and the south polar ice cap into vast neutrino observatories by submerging long strands of light-sensing tubes in the water and ice.

Another idea is to go small but accurate. Crystal-germanium in the Cryogenic Dark Matter Search (CDMS) detectors built at Stanford University can ignore every known particle bouncing off the lattice. Now they are listening for the off-key ping of dark matter in a room 40 feet (10 meters) underground. An even more sensitive experiment, CDMS II, began operating in late 2003 in a Minnesota iron mine 2,400 feet (740m) underground.

In 2000, researchers on the Italian Dark Matter Experiment (DAMA) team claimed to have found dark matter, but that result was widely discounted when other investigators were unable to confirm the finding. Meanwhile, experiments proceed in the United States, Italy, Germany, and Japan, but no one has found unequivocal evidence of the dark matter particles that are supposed to be so abundant.

6 Are all the baryons assembled in galaxies?

Only 10 percent of the normal matter in the universe — baryonic matter made of protons, neutrons, and electrons — is in stars. Astronomers are trying to find more baryons with quasars — brilliant objects at great distances from Earth that are powered by black holes. If quasar light passes through baryons in the form of gas on its way to Earth, the atoms in the gas would leave their imprint on the quasar spectrum as absorption lines. But astrophysicists have found a tiny fraction of what they expect. Where have all the baryons gone?

Nowhere, say most astrophysicists; they are still floating in space. But in the billions of years since the gas clouds formed, they would have collided with each other, launching shock waves to heat the gas to around a million degrees Celsius. "It is an unfortunate coincidence," says Princeton University astrophysicist Jerry Ostriker, "but gas in that temperature range doesn't emit or absorb radiation strongly," which means astronomers can't easily detect it.

David Weinberg and his collaborators tried to find evidence of the gas in dark matter halos that surround galaxies while using the Chandra X-ray Observatory for a week in 2001. Weinberg is 90 percent confident they saw traces of the gas through X-ray absorption data but says he'd need to look for an even longer period to be sure. "That's a lot of

THE VAST GAPS BETWEEN GALAXIES may not be empty. Astronomers using the Chandra X-ray Observatory will look for "missing" gas in them. *ASTRONOMY:* ROEN KELLY

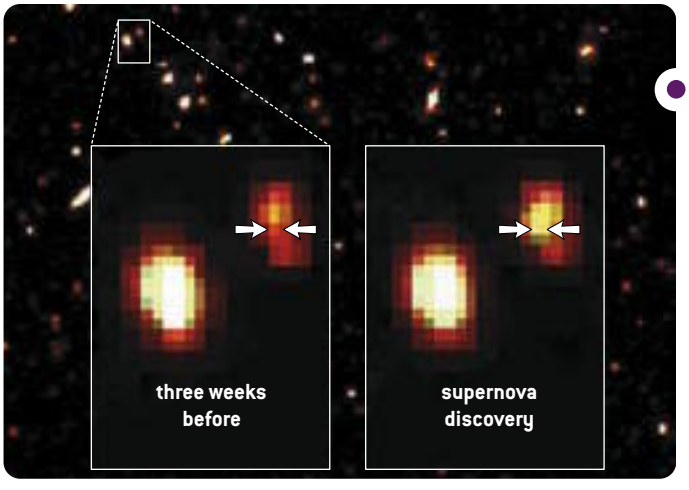
telescope time to devote to a single observation that might detect nothing," he admits. "But this could be the best way of figuring out where the baryons are today. It's a basic issue of cosmic accounting."

7 What is dark energy?

To get enough oomph to drive the present acceleration of the universe, dark energy must make up about 73 percent of the total density of the universe. The biggest problem with this idea is that no one has any idea what dark energy is. "So far, all we've been able to do is name it," says the University of Chicago's Michael Turner. "It could be the energy associated with nothing [i.e., the vacuum of space itself] or the influence of hidden spatial dimensions."

At least astronomers know what it does. "It is repulsive like antigravity," says Perlmutter. "But it is not a force in the sense that it doesn't depend on the properties of the particles themselves. It acts directly on space." The general "springiness" of space is a bit like the inflationary expansion of the infant universe, except that dark energy exerts a much smaller influence over a much longer time.

Physicists have tried to calculate the density of dark energy from accepted theories of physics, but their results don't jibe with reality. So far, the computed value is roughly 1,060 times greater than the observed value. (Others say the number could be off by a factor of up to 10,120, but let's not quibble over the fine print.) Cosmologists are used to dealing in large numbers, but even they find the discrepancy worrisome. All those zeroes, says Kolb, "tell us that something fundamental is still missing from our theories."



DISTANT SUPERNOVAE, used as "standard candles" to measure intergalactic distances, gave astronomers evidence that the expansion of the universe is accelerating. SAUL PERLMUTTER, SUPERNOVA COSMOLOGY PROJECT

8 What is the destiny of the universe?

Most of the matter and energy in the universe resists expansion. If it had its way, the gravitational force of this material eventually would collapse the entire universe into a point. But dark energy makes the universe grow. Indeed, the fate of the universe is unknown because our understanding of dark energy is sketchy.

Dark energy is responsible for the current acceleration of the universe's expansion. And if the density of dark energy is a universal constant, or at least remains positive throughout the universe, then dark energy wins. The universe will continue to expand at a steadily increasing rate so that in 100 billion years, we would be able to see only a handful of galaxies with today's telescopes.

IF THE EXPANSION OF THE UNIVERSE continues, as most cosmologists now believe it will, space will become a cold, lonely place tens of billions of years from now. JAMES HERVAT

But dark energy — Einstein's famous cosmological constant — might actually be variable. It is even conceivable that it could become negative, which would make the universe collapse. "Even a change to a small negative value of the cosmological constant could make the whole universe collapse again," says Cambridge University astrophysicist Martin Rees.

At the moment, no telescope can see far enough to tell us which possibility is correct. In cosmological terms, the most distant supernovae studied so far to probe the density of dark energy are our next-door neighbors. But researchers are counting on the proposed SuperNova/Acceleration Probe (SNAP) satellite to remedy the situation. Orbiting far above the obscuring atmosphere of Earth, the dedicated supernova-hunting telescope will push the dark-energy frontier at least halfway back to the Big Bang in the hopes of settling this cosmological question once and for all.

The deep end of cosmology

The eight mysteries of modern cosmology presented here are deep enough to perplex cosmologists without being so deep as to appear unanswerable. And if good fortune continues to smile on cosmology as it has in the past century, many scientists are betting these questions may be answered by 2010. Does that prognosis mean cosmology is a problem on the verge of being solved?

Absolutely not. If cosmologists have learned anything, it's that every answer generates another question. A

Into the ever-st CO

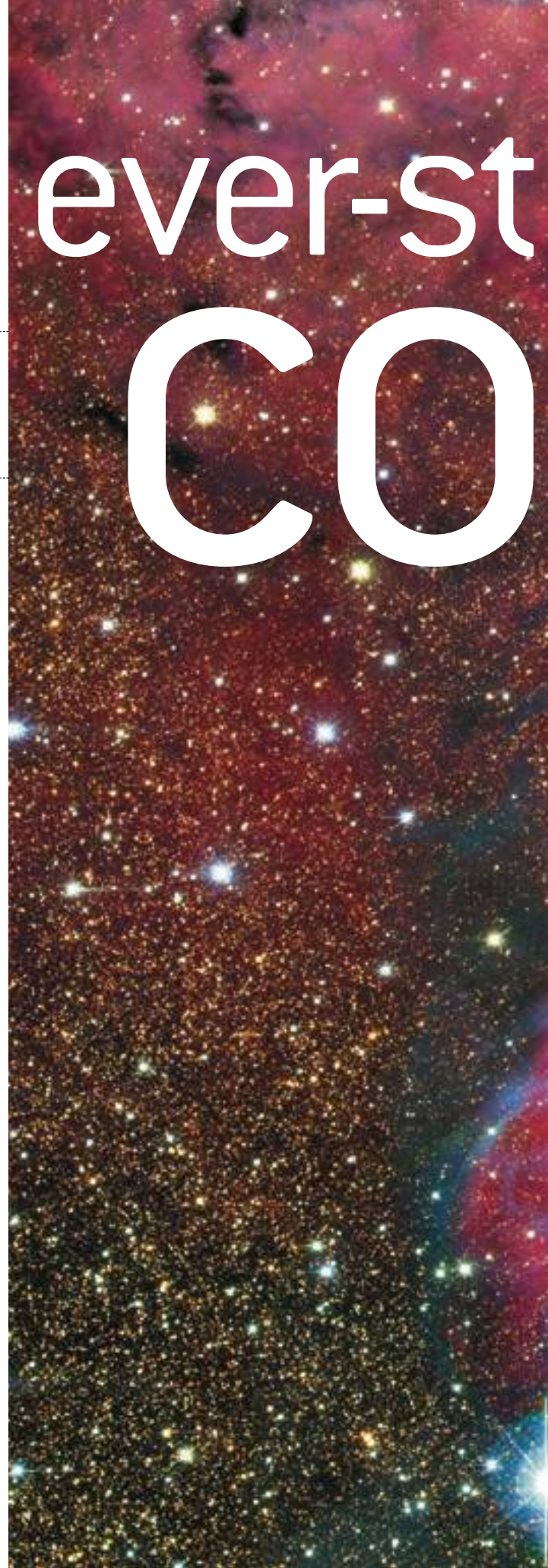
The deeper astronomers look, the stranger the universe appears, with ever-weirder stars and galaxies. /// BY CHRISTOPHER CONSELICE

Not long ago, the universe seemed like a simple place. At the turn of the 20th century, astronomers were unaware of the existence of galaxies, quasars, and black holes. With a backdrop of twinkling points and fuzzy nebulae littering the sky, the universe was thought to consist of our solar system, the Sun, planets, asteroids, and comets, floating in a lonely void of distant stars.

Anyone with even a casual knowledge of astronomy knows that the astronomical zoo has grown so explosively that we now know of hundreds of types of objects inhabiting the cosmos. But does that mean the universe is a complicated place? Not as much as you might think. Most of the hundreds of types of celestial entities are related to each other and can be woven together in a common fabric. Understanding these objects, their origin and evolution, is the focus of much of modern astronomy. By learning about the individual pieces that make up the cosmos, astronomers can also gain insights on the universe as a whole.

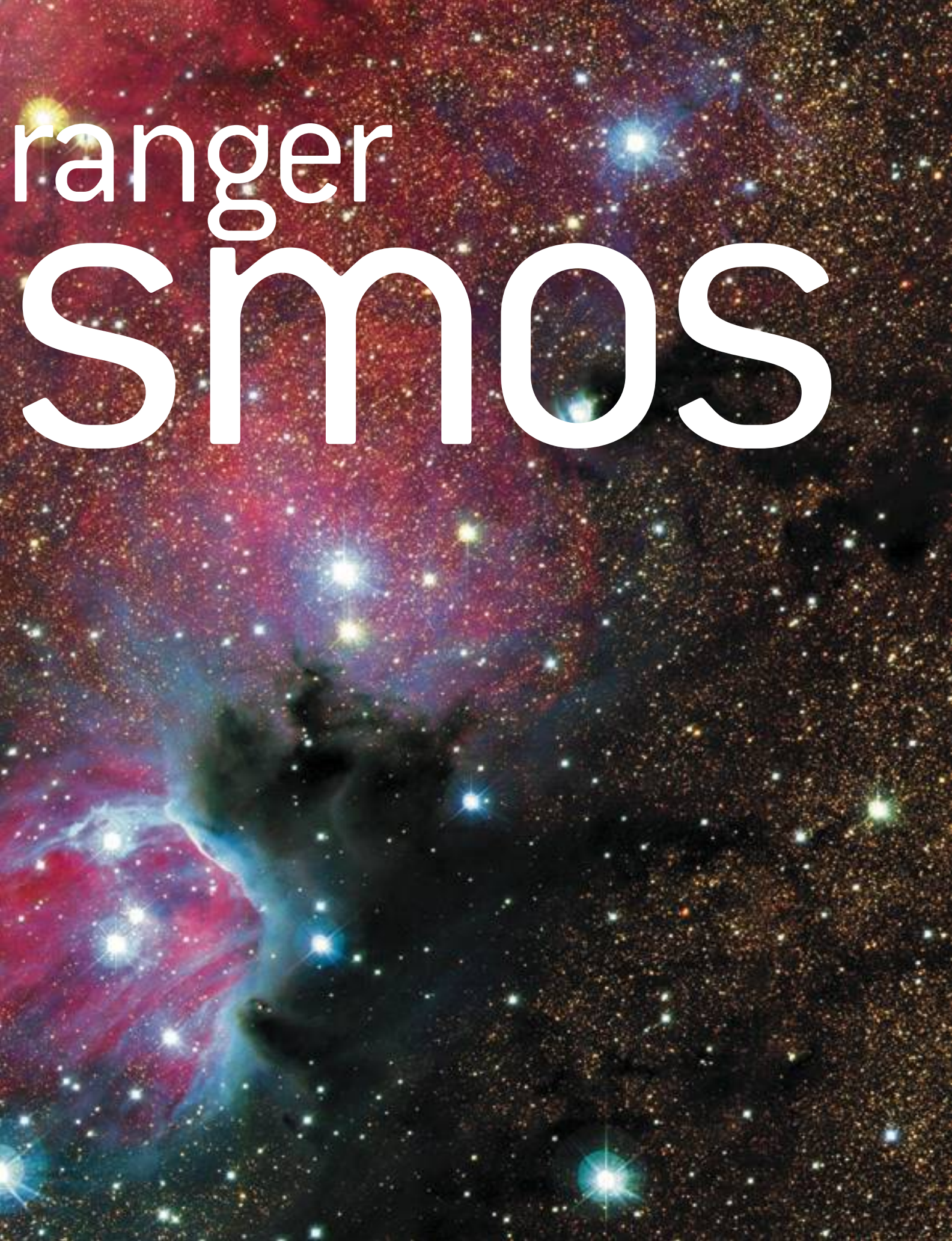
The largest structures in the universe, galaxy clusters, hold thousands of galaxies together in their gravitational grip like bees swarming around a common center of mass. Recognized in the 18th century by William Herschel and Charles Messier — although thought to be clumps of nebulae — galaxy clusters offer astronomers lots of information about the early universe. A single galaxy cluster is roughly a thousand times more massive than the Milky Way. Most of the galaxies in clusters, however, are low-mass objects with dark and mysterious backgrounds; astronomers don't yet understand how they came to be. Galaxy clusters contain all manner of galaxies, but the densest clusters contain galaxies with the oldest stars. The oldest clusters found to date are roughly 8 billion years old, more than half the age of the universe. Although astronomers have seen galaxies even older than that, none of those ancient galaxies have yet congregated into clusters.

Clusters are important to astronomers not only because they host galaxies, but also because they contain vast amounts of matter. They act as natural laboratories, allowing astronomers to see how



A STELLAR NURSERY, IC 4678 in Sagittarius consists of a blanket of molecular clouds slowly condensing and churning out infant, white-hot stars in a sparkling cluster. JEAN-CHARLES CUILLANDRE, CFHT

Updated from *Explore the Universe 2003*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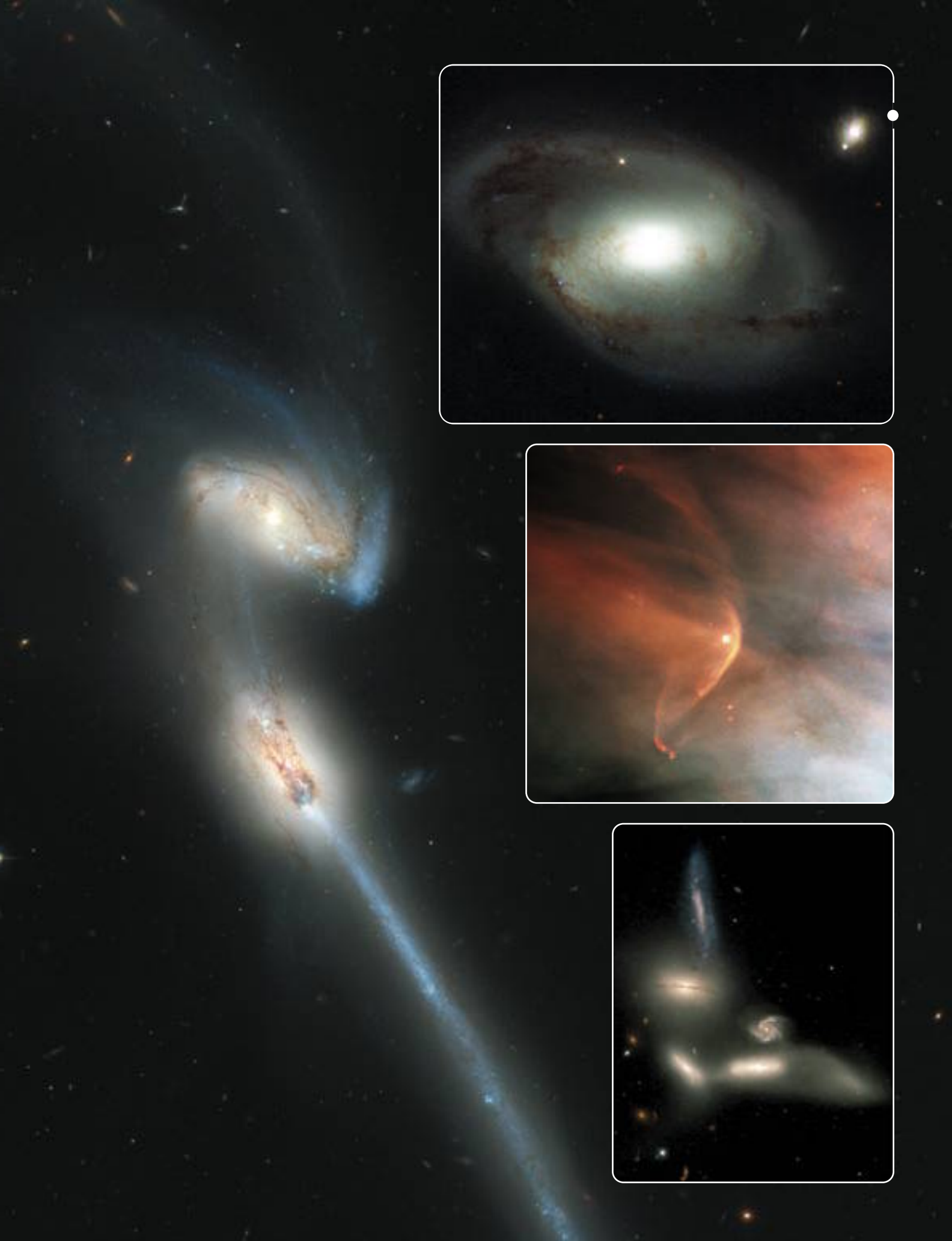

OPALESCENT COLOR marks the oddly-shaped Egg Nebula, where a dying star is casting a searchlight beam outward into onion-skin layers of dust surrounding it. The star lies entombed in a thicker, vertical belt of dust that enshrouds its brilliance. NASA/STScI

the mass in galaxies interacts with that in others. They also contain an extensive collection of gas and dust. In fact, galaxy clusters contain enough mass that they can be used as gravitational lenses — bending the light from distant galaxies that lie behind them to form secondary images.

While some astronomers focus on galaxy clusters, legions study individual galaxies. Although many galaxies are found in clusters, most are found in smaller collections of objects, as with the Milky Way's membership in a little cloud of galaxies called the Local Group. The Local Group holds at least 39 galaxies in a sphere measuring roughly 10 million light-years across. Aside from the Milky Way, the predominant members of the Local Group are the Andromeda Galaxy (M31) and the Pinwheel Galaxy (M33) in Triangulum. As Edwin Hubble viewed these and other galaxies in the 1920s, he found the most common types of galaxies are spirals, like M31 and M33, or ellipticals, enormous spherical balls of stars, gas, and dust.

But many other types of galaxies exist, with active galaxies constituting an important class. As their name suggests, active galaxies are highly energetic places with giant black holes in their centers. Active galaxies go through periods of "grazing," when matter falls into the black hole and later gets flung outward in violent jets. Equally remarkable are starburst galaxies — objects that are undergoing periods of extreme star-production. Astronomers have found that the most common type of galaxy, however, at least in the nearby universe, is the dwarf. Dwarfs are small, faint, low-mass systems that were probably the first galaxies to form.

The easiest place to start a tour of galaxies is with the brightest examples, thousands of which are available for viewing in backyard telescopes. In any clear, dark evening sky, dozens of bright galaxies are visible — particularly in the spring and autumn. Elliptical galaxies are among the easiest to view by amateurs because they have high surface brightnesses; their round or elliptical glows stand up well under magnification. Ellipticals are composed of old stars and contain little evidence of dust, young stars, or hydrogen gas. Most of the stars in ellipticals are older than 8 billion years. Ellipticals are most commonly found in clusters and typically have masses several hundred times that of the Milky Way.

Spiral galaxies are certainly the most easily recognized type. Our own galaxy is a spiral, as are the Andromeda and Pinwheel galaxies. Most spiral galaxies, including the Milky Way, have features such as bars and rings. The Milky Way is classified as a barred spiral. These bars and rings, which form by dynamical effects such as interactions with other galaxies, are often associated with regions of star formation. The spiral arms in these galaxies contain large amounts of young stars and significant clouds of dust and gas. The young, blue stars within spiral arms give these features their distinctive appearance. Spirals usually have a bright central area known as a bulge, which emits a smooth glow similar to elliptical galaxies. Most astronomers now believe that the bulges of spiral, as well as elliptical, galaxies probably formed from the mergers of many smaller galaxies.

INTERTWINED PARTNERS, galaxies NGC 4676A and NGC 4676B (opposite page), are locked in a gravitational dance that carries them together through space. Galaxy NGC 4319 partners with quasar Markarian 205 (opposite, top inset). LL Orionis blows a fast wind that sculpts surrounding gas clouds (opposite, center inset). Galaxy group Seyfert's Sextet holds six galaxies locked together in space (opposite, bottom inset).

NASA/STScI; NASA AND THE HUBBLE HERITAGE TEAM; NASA AND THE HUBBLE HERITAGE TEAM; NASA/STScI

The small, the meek, and the disturbed

Not all galaxies are so graceful and well behaved as spirals and ellipticals. Starburst galaxies, the objects undergoing episodes of high-powered star formation, are more explosive and enigmatic. The blast of star formation takes place when gas clouds inside these galaxies collide, get compressed, and subsequently make stars. The riddle of how these gas clouds collide is a major focus of extragalactic astronomy.

Several methods might be responsible for producing starburst galaxies. One mechanism involves interactions with other galaxies. When two galaxies collide, as with the Antennae (NGC 4038–9) in Corvus, the gas they contain compresses, which brings

A MIGHTY GLOBE OF SUNS, globular star cluster M80 floats majestically in the outer halo of the Milky Way Galaxy. Nearly a million stars are grouped together in this sphere, and they are ancient — among the original generation of stars, dating to the early days of the universe. NASA/STScI

enough matter together to make new stars. Astronomers who've studied galaxies like the Antennae are excited now that they're seeing extremely distant (and hence ancient) galaxies that appear to be undergoing starbursts in the same way. Starburst galaxies in the nearby universe might be the best analogs we have to the brightest galaxies in the early universe.

Active galaxies powered by black holes also offer great opportunities for astronomers to learn how galaxies work. This class includes many specialized classes of galaxies, including BL Lacertae objects, quasars, and Seyfert galaxies. The differences among these types of active galaxies stem from their brightness but also may relate to the angle from which we view them. They all work basically the same way, with material falling into the black hole, which, in turn, accretes gas from the galaxy. This produces great amounts of light and other radiation streaming out from the galaxy's center. The central portion of a quasar, for example, can be several hundred times brighter than that of a normal galaxy.

The third major type of galaxy, dwarfs, constitutes the most plentiful type found in the nearby universe. Dwarf galaxies outnumber their larger counterparts by at least a factor of 10 but are factors of 100 to 1,000 smaller and less massive than normal elliptical and spiral galaxies. Two basic types of dwarfs exist — dwarf ellipticals and dwarf irregulars. Dwarf irregulars are tiny galaxies undergoing miniature bursts of star formation. Their fundamental difference from starbursts and spiral galaxies lies only in scale. These galaxies generally don't contain spiral arms, as their mass is too small to sustain this kind of dynamic.

Dwarf ellipticals, the most common type of small galaxy, generally form in dense areas such as galaxy clusters. They contain mostly old stars, just as giant ellipticals do, but are much fainter than normal elliptical galaxies. Current research on dwarf ellipticals has identified several possible formation mechanisms. Understanding how dwarfs, now known to be the most common type of galaxy, came to be will be critical to unlocking the secrets of how all galaxies formed and evolved.

Peeking inside

Inside galaxies lie numerous kinds of objects, including stars, an interstellar medium of gas and dust, planets, and — at least in our own solar system — life. Stars come in many different types, just as galaxies do. Most stars are burning hydrogen in their cores, including all the stars we see in the night sky. The brightness and color of each star depends on its mass and age.

Exceptions always exist, but massive, young stars generally are bright and blue while older, low-mass stars are redder. There's more to the story, however, as astronomers now know that very faint stars with low masses exist. These so-called dwarf stars, which come in two types, either brown or white, have masses between only 10 percent and up to 1.4 times that of the Sun.

As a source of exotic new objects, few events top the deaths of stars. Three basic scenarios unfold when a star reaches the end. If it is very massive, roughly more than 8 times the mass of the Sun, it explodes catastrophically in a supernova and the stellar remnant becomes either a black hole or a neutron star. Of these massive stars, those with the highest mass become black holes; the lower mass ones become neutron stars. These stars are so dense that atomic nuclei become pressed together into a virtually solid object. Because neutron stars rotate, they beam periodic pulses of energy. We call these objects pulsars.

A lower-mass star like the Sun meets a different fate. The star loses the outer parts of its structure, making a glowing shell of gas called a planetary nebula, and leaves behind its remnant as a white dwarf. White dwarfs are very faint, hot objects with temperatures of 10,000 kelvins and intrinsic brightnesses only $\frac{1}{10,000}$ that of the Sun. They are similar in size to Earth. The most famous

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WRAPPED IN WARM GAS, newborn stars in the dusty nebula IC 1396 in Cepheus blaze radiation into the surrounding cosmos. A new cluster will emerge from this dusty cocoon. JEAN-CHARLES CUILLANDRE/CFHT

THE SOMBRERO GALAXY offers the classic edge-on look of a looming spaceship. It contains enough mass to make 800 million suns, spans 50,000 light-years end to end, and lies 28 million light-years away in the Virgo cluster of galaxies. NASA/STScI

white dwarf, and the first discovered, is the companion star to Sirius, called Sirius B. It was discovered in 1862.

What about planets and other objects that orbit stars? Astronomers have now cataloged more than 120 extrasolar planets. Some of these orbit a common star, meaning that other solar systems beyond ours are known to exist. Many of these planets are very massive — several times heavier than Jupiter, the most massive planet in our system. The orbits of these planets appear to be very different than those of our solar system; many have very eccentric orbits rather than the nearly circular orbits of our neighboring planets. Astronomers don't yet know a lot about extrasolar planets. They know that one planet circling the star HD 209458 has an atmosphere because it was detected by means of sodium absorption. And the planet recently has been detected shedding oxygen and carbon.

Our knowledge about planets comes almost entirely from our own solar system. We have nine planets here but also a large number of additional bodies orbiting the Sun. The nearest of these are asteroids, which are principally found between Mars and Jupiter and have very small sizes and masses. The largest asteroid, Ceres, weighs about 1/5,000 of what Earth weighs. A range of asteroids exists, most consisting of some combination of silicates and metals such as nickel and iron. Several asteroids are known to have satellites, just as planets have moons, or to be binary or two-lobed objects. Asteroids can be found throughout the solar system; they were probably among the first clumps of stuff to form in the inner solar system and generally resemble the planetesimals that later accreted into the much-larger planets.

The solar system doesn't stop there. Numerous comets and Kuiper Belt objects also careen through the neighborhood. Comets, with their gauzy tails glowing as they approach the Sun, are well known to astronomers and non-astronomers alike. Comets are essentially dirty snowballs, with rock, ice, and gas frozen into a nucleus that orbits the Sun in periods ranging from a few years to several hundreds of thousands of years. Most comets sublimate away after a billion years, but new comets originating from the Oort Cloud on the distant fringes of the solar system replenish the supply.

Kuiper Belt objects, which orbit lazily beyond Pluto, are a separate breed. Astronomers now know of some 800 Kuiper Belt members and believe that tens of thousands may exist. Studying these objects will help solve mysteries about the origin and evolution of the solar system because they may be composed of pristine material from the earliest days of its formation.

THE RUBY RED GLOW of the star-forming region IC 5146 in Cygnus, called the Cocoon Nebula, surrounds a small cluster of infant stars that sparkle through the hydrogen gas surrounding them. JEAN-CHARLES CUILLANDRE/CFHT

Remaining mysteries

What else does the universe hold? Is anything out there that we can't observe? The answer is undoubtedly yes. All the objects described thus far emit or reflect visible light. But this diversity represents only a small fraction of the matter in the universe. More than 99 percent of matter in the cosmos exists in nonstellar form. Most of it consists of dark matter whose nature is anyone's guess. Several features about dark matter are known. It appears to be attached to galaxies and, whatever it is, astronomers generally agree it is cold, meaning the particles that make up dark matter are not moving very fast. Using this information, astronomers can perform computer simulations that reproduce the structure of the universe, reinforcing their belief that dark matter is cold.

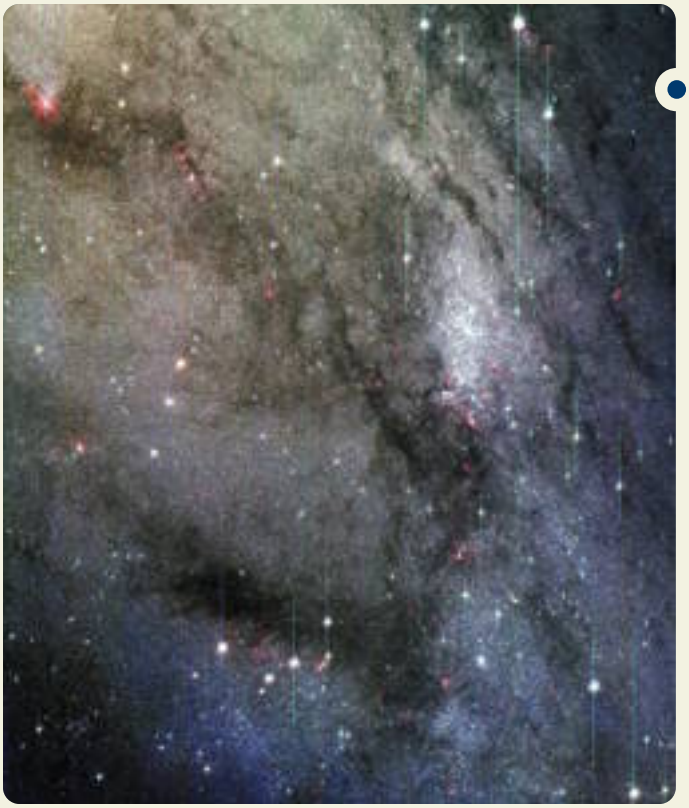
Very recently, astronomers hypothesized that a tremendous amount of so-called dark energy exists, and that it is pushing — and accelerating — the expansion of the universe. As the evidence mounts, astronomers now believe that dark energy is, in fact, the force driving the acceleration.

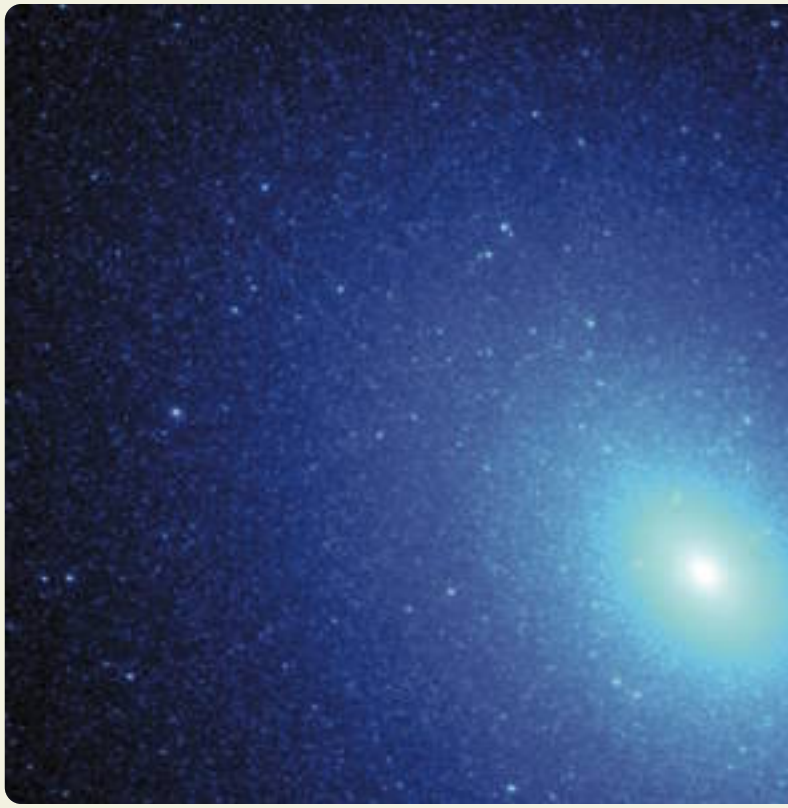
We have much to learn about how dark energy and dark matter relate to known astronomical objects. But the universe is also likely to contain many objects that are far more exotic than those we currently know about. The next time you're out under the stars, gazing at some galaxy or nebula with your telescope, remember that it's only a matter of time — and newly acquired insights — before the universe looks very different to us than it does today.

local group GALAXIES

THE LOCAL GROUP IS A CLUSTER of about 40 galaxies to which the Milky Way belongs. Three large spirals dominate it with their gravity: the Milky Way, Andromeda (M31), and Pinwheel (M33) galaxies. The rest of the Local Group's population consists of small dwarf ellipticals and irregular galaxies. In 1923, Edwin Hubble's identification of Cepheid variable stars in M31 was the key step in discovering the expanding universe.

Above, **THE PINWHEEL GALAXY (M33)** /// T. A. RECTOR, M. HANNA/NOAD/AURA/NSF





Top left, **THE ANDROMEDA GALAXY (M31)**
/// SUBARU TELESCOPE

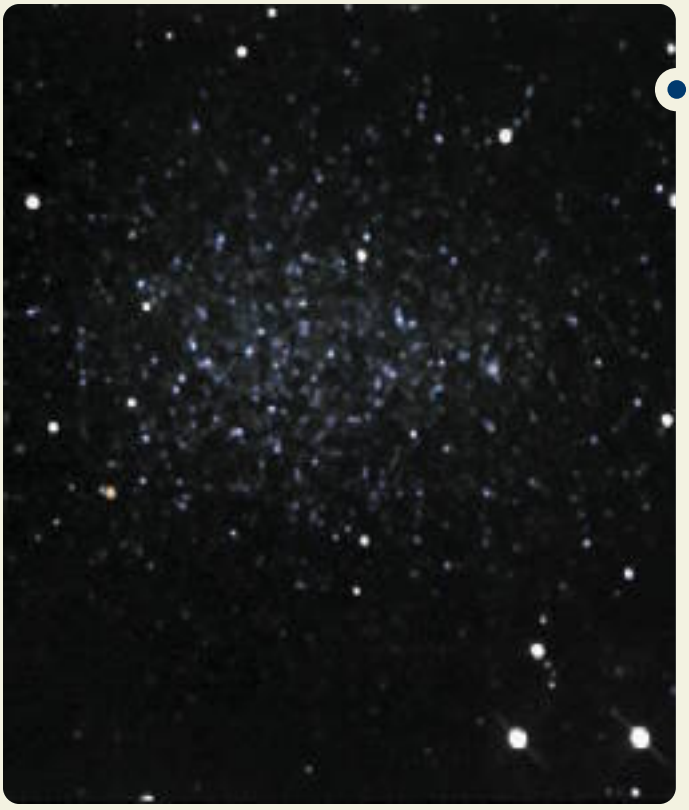
Top right, **M32** /// STScI

Above, **THE ANDROMEDA GALAXY (M31)**
/// TONY AND DAPHNE HALLAS

Top left, **THE ANDROMEDA GALAXY (M31)**
/// ROBERT GENDLER

Top right, **NGC 205 (M110)** /// ROBERT GENDLER

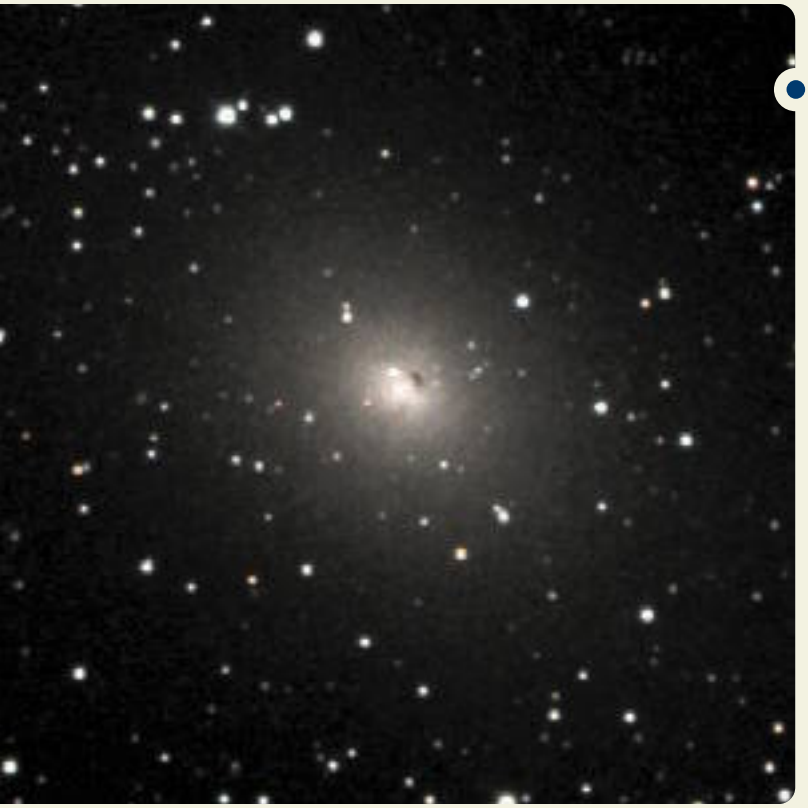
Above, **THE PINWHEEL GALAXY (M33)**
/// TONY AND DAPHNE HALLAS

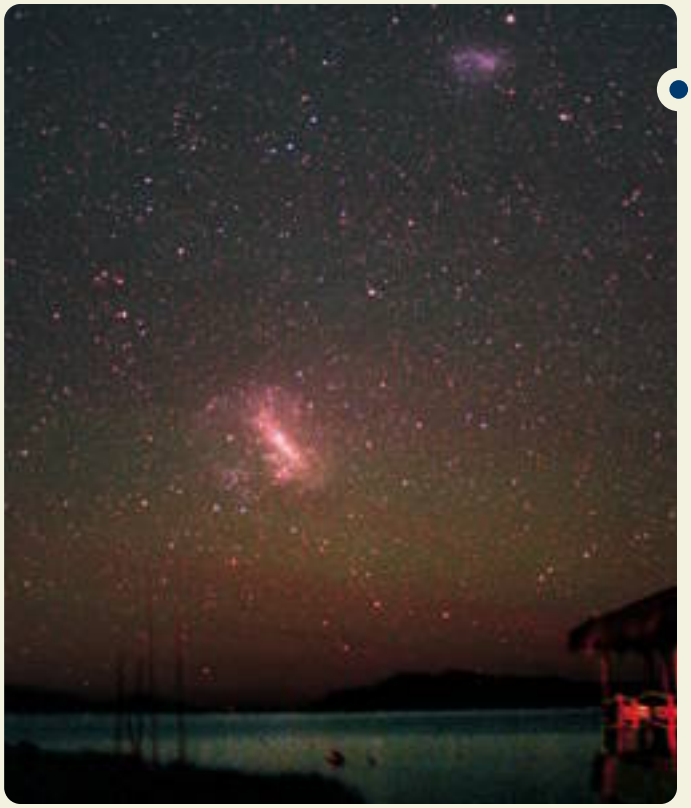


Top left, **LEO I** /// CHRIS SCHUR

Top right, **IC 10** /// CHRIS SCHUR

Above, **MAFFEI 1** /// CHRIS SCHUR

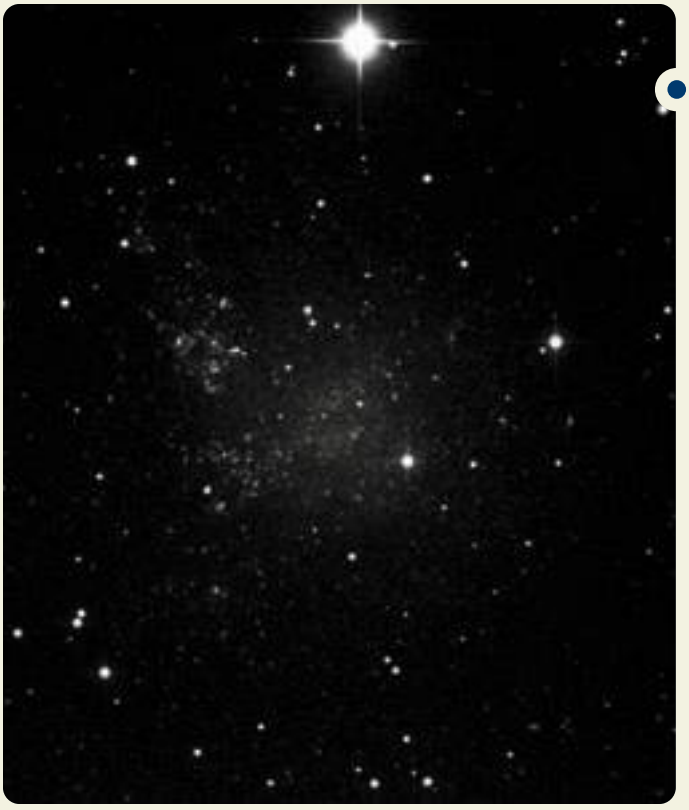




Top left, **NGC 185** /// CHRIS SCHUR

Top right, **LARGE (left) AND SMALL (right) MAGELLANIC CLOUDS** /// FRED ESPENAK

Above, **SMALL MAGELLANIC CLOUD AND GLOBULAR CLUSTER 47 TUCANAE** /// FRED ESPENAK



Top left, **IC 1613** /// MARTIN GERMANO

Top right, **NGC 6822** /// MARTIN GERMANO

Above, **LARGE MAGELLANIC CLOUD** /// FRED ESPENAK

THE BUDDING UNIVERSE, much too small yet to be visible, began to expand faster than the speed of light. In a minuscule part of a second, the universe doubled in size 100 times. But almost as quickly as it began, this process called inflation ended, releasing energy destined to become radiation and matter. ILLUSTRATIONS: *ASTRONOMY:* ROEN KELLY

Inflation comes of age

More than two decades after cosmic inflation transformed cosmology, one important question remains: Is the universe a bigger place because of it? /// BY STEVE NADIS

On December 7, 1979, a relatively unknown young Stanford University physicist named Alan Guth hit upon an idea so powerful, he penned the words "spectacular realization" on a leaf of his equation-strewn notebook. Within a year, the scientific community recognized that Guth's idea was spectacular indeed. After all, Guth's tinkering with the tenets of particle physics had single-handedly cracked many of cosmology's unsolved riddles.

Guth's grand idea, which he called inflation, seemed to be just what was needed to mend gaping holes in Big Bang theory at the time. In 1979, the standard Big Bang model adequately explained the origin of light elements and the presence of the cosmic microwave background (CMB) left over from the primordial blast. But the standard model fell short on answering several important questions: Why is the universe so uniform on the largest length scales? What caused fluctuations in the matter density of the universe that ultimately led to the formation of galaxies, planets, and people? And why does the universe contain so much matter?

Now, more than two decades after Guth's eureka moment, it's worth investigating how well inflation has stood the test of time. On the one hand, inflation is doing well, widely considered an integral component of Big Bang cosmology. Yet on the other hand, it still suffers from vagueness. "Although the basic idea still looks very attractive," admits Guth, "we don't know the real details of inflation or the mechanism that drives it." Astronomers, meanwhile, are still trying to determine whether inflation will prevail, require modification, or be replaced. The possibilities, as you'll see, are nearly infinite.

As cosmological concepts go, inflation's roots are pretty straightforward. A basic prediction from particle physics states that matter at very high energies (like those expected during the universe's birth) can assume a variety of unusual forms, including one state that turns gravity upside down. In this case, massive particles repel rather than attract each other. What's more, matter in such a topsy-turvy state possesses another strange property: Its density remains constant, even as the volume of space it inhabits expands like mad.

In the parlance of particle physics, such a space-filling, antigravity substance can be

Updated from the April 2002 issue of *Astronomy*

/// ALAN GUTH: REINVENTING THE PAST AT MIT

In 1980, when Alan Guth first shared his ideas about inflation (a term he coined) with the scientific community, cosmology was soon transformed, but not as quickly as Guth's own life changed. At the time, he was a postdoctoral researcher at Stanford with "uncertain" job prospects, at best. "My impression is that people thought I looked smart but hadn't done anything important," recalls Guth. "Looking smart had gotten me really good appointments so far — including graduate school at MIT and post-docs at Columbia, Cornell, and Stanford — but things didn't look good for me getting a teaching job at a top-notch institution."

Within a few months of his public pronouncements on inflation, Guth received calls from ten universities offering jobs. He joined MIT's faculty that same year, earning tenure three years later. Meanwhile, Guth became a celebrity of sorts, "receiving more than my share of attention," as he puts it. His notebook, with the words "spectacular realization" written on it, is now on display at the Adler Planetarium in Chicago. He joined the National Academy of Sciences in 1989 and won the 2001 Benjamin Franklin Medal in Physics — an award that has been granted to such luminaries as Albert Einstein, Stephen Hawking, and Edwin Hubble.

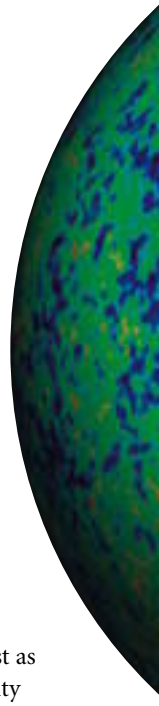
One price of fame is that Guth now has very little time to do physics. "The number of letters of recommendation I've been asked to write, for example, continues to escalate," he says. "I always fret about those letters, trying hard to say the right thing." The late-night, early-morning hours of around midnight to 4 A.M. (which is when he had the "realization" that started all this) is about the only time people leave him alone. Even then, he's occasionally accosted by MIT students trying to make appointments to see him.

Guth gets by on little sleep — sometimes only a few hours a night — in order to keep abreast of developments in physics and pursue his own theoretical musings. "The work itself mainly consists of sitting and thinking through equations," he explains. "First, one needs an idea of what to calculate. That comes by paying attention to your field and noting gaps that, if filled, could push things forward."

Asked whether he feels strange contemplating the beginning of the universe when almost everyone around him is fast asleep, Guth replies, "Working at 4 A.M. doesn't seem absurd to me. But working on theories about the first 10-to-the-minus-35th second can seem absurd at any hour. The only thing that changes that is time spent on the problem. In the long run, when some data actually agrees with these wild speculations, one begins to think we might be on the right track after all."

For the past twenty-plus years, Guth has devoted himself almost exclusively toward establishing a workable theory of inflation. "If this idea is right, it's an important step in the process of discovering that everything about the universe, including its creation, is subject to the laws of physics and can be explained in terms of physics," he says. "We're not there yet, but if it does work out, I'd consider it a mind-boggling achievement."

It's more than a full-time job, especially in view of Guth's growing obligations as a teacher, lecturer, and leader in his field. But he occasionally steals a few moments for fun. One favored pastime, which provides welcome relief from physics, is working on math problems with his son, Larry, an MIT graduate student.



described by a scalar field. Although it may sound exotic, a scalar field is merely a way of representing an array of numerical values at various points in space. For example, if you can quantify a particular parameter at multiple locations, such as air pressure at every spot in a room, you've got an air pressure scalar field. Moreover, scalar fields (so far as particle physicists are concerned) are subject to quantum fluctuations. And if fluctuations in the antigravity scalar field become large enough, a region of space can expand rapidly. If even the tiniest patch of space is filled with an antigravity scalar field, for a brief moment it will swell uniformly and exponentially, like a loaf of bread rising at warp speed.

According to Guth's inflationary model, an antigravity scalar field dominated the universe when it was just 10^{-35} second old. Fluctuations in this field caused the budding universe, then smaller than the size of a proton, to expand faster than the speed of light. And in the course of roughly a trillionth of a trillionth of a trillionth of a second, the universe doubled in size a hundred times over. But almost as quickly as it began, inflation ground to a halt as the antigravity material became unstable, eventually releasing energy transformed during the inflation-induced expansion into radiation and matter. Finally, the universe continued to expand at the much more moderate, yet apparently accelerating, pace we observe today.

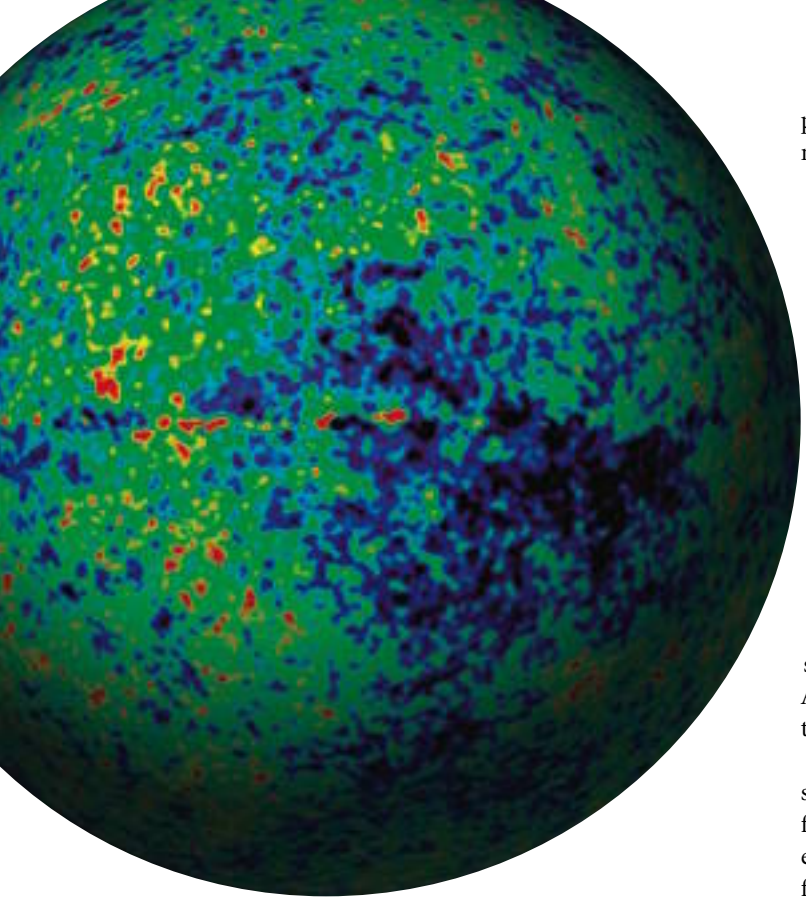
Jell-O and chaos

Despite its initial success, inflation has never been immune from criticism. Guth's initial formulation, for example, had a crippling weakness, which he acknowledged in his original 1981 paper and explained at greater length in a subsequent paper written with Erick Weinberg of Columbia University. Guth mistakenly pictured the phase transition between the antigravity era and the radiation-dominated era that followed as something akin to water boiling. In this scenario, the post-inflation universe was filled with "bubbles" that never had a chance to collide and merge owing to the rapid expansion. "The formation of these bubbles would have made things so inhomogeneous, it would look nothing like the universe we see," says Guth.

The first successful way around that problem, called "new inflation," was devised in late-1981 by Andrei Linde, a physicist now at Stanford, and independently by Paul Steinhardt and Andreas Albrecht, now at Princeton and the University of California, Davis, respectively. "The boiling of water was replaced by a milder, slower transition, which was more like the congealing of Jell-O," Guth says. That slowed down the pace of inflation, giving each bubble the chance to expand to fantastic dimensions, far bigger than the observable universe. If this view is right, says Guth, "we're living inside a bubble so large, we couldn't possibly see the edge."

Steinhardt and his colleagues developed another prescription for stalling inflation by adjusting the behavior of the antigravity scalar field, which physicists also describe in terms of its potential energy. When the field is at its maximum potential energy, it's like a ball on top of a hill. As the system moves toward equilibrium, in the same way that a ball naturally rolls downhill, its potential

Steve Nadis, *who edited this issue, is a contributing editor and freelance writer based in Cambridge, Massachusetts.*



WITHOUT INFLATION, astronomers would be hard-pressed to explain the cosmic microwave background's startling uniformity, which deviates from perfection by less than one part in 100,000. NASA/WMAP SCIENCE TEAM

energy becomes kinetic energy. The kinetic energy, in turn, is converted to radiation, which ultimately halts inflation. As a bonus, some of that radiation later gets converted into matter that fills the universe.

Nevertheless, Linde later rejected new inflation after realizing that the universe need not have been spawned from a hot, dense phase as the Big Bang model predicts. In 1983, he proposed a modification called "chaotic inflation." (Incidentally, Steinhardt and Guth, among others, still consider new inflation viable.) The basic premise of chaotic inflation is that, out of sheer randomness, the scalar field can have a variety of energy values. In some places the scalar field is sitting at its "ground state," near the potential energy minimum, while at other places it happens to possess more potential energy. The region of space near the minimum stays small and doesn't inflate, whereas the region with excess potential energy inflates and becomes exponentially large.

Despite its name, the concept has nothing to do with "chaos theory," which describes unpredictable systems that grow increasingly disordered over time. "This is really the opposite," Linde says. "Here you start with chaos and end with perfection."

In 1989, Steinhardt and his graduate student, Daile La, introduced the notion of "extended inflation," which offered a new way to end inflation by proposing changes in the behavior of gravity at high energies to slow the universe's expansion. A host of other inflationary models have since been proposed, including "hyper-extended inflation," "open inflation," and "two-round inflation." All these models attempt to explain three things: How does inflation start, what drives it, and how do you end it? "It's like a Chinese menu," Steinhardt says. "You have a couple of choices for parts A, B, and C. Although the number of concepts isn't that great, you can put them together in many different ways."

It might seem surprising that models missing key details — such as the energy scale at which inflation proceeds — can perform so well (see "Inflation flattens the universe," below). "Oddly enough, we can make accurate predictions even though we don't fully understand the mechanism behind inflation," says Guth.

Surfing the CMB

But how do we go about separating the most plausible models from the more dubious ones? "We can rule out most inflationary theories simply by studying the microwave background in greater detail," says Linde. Those tests can help narrow down the field, Guth agrees, "but we will not find a unique solution from any experiments that are currently planned."

Meanwhile, astronomers are pinning their hopes on gravity waves produced in the universe's first moment as our best chance for studying the conditions that triggered inflation. There's no prospect of seeing the most energetic gravity waves directly because they would span the entire universe and it would take an instrument at least that big to detect them. The strategy, instead, is to look for the subtle impressions these waves would make on the CMB. The imprint of gravity waves was not apparent in the first year's data released by the Wilkinson Microwave Anisotropy Probe (WMAP), but it may be spotted during the next three years of data

/// INFLATION FLATTENS THE UNIVERSE

In the last few years, the theory of inflation has received a welcome boost from several research collaborations observing the ubiquitous cosmic microwave background (CMB), remnant radiation from the creation of the universe. As it turns out, small temperature variations in the CMB speak volumes about the geometry of the universe. The accepted reason is that these variations are blown up and accentuated by inflationary expansion. Inflation would, of course, suffer a fatal blow if the theory did not mesh with CMB observations.

The geometry of the universe can take one of three states depending on the overall density of matter. If the density is equal to a benchmark called the critical density, the geometry is flat, like a sheet of paper. If the density is above or below critical, the geometry is either postively curved (like the surface of a sphere) or negatively curved (like the surface of a saddle), respectively. Multiwavelength observations indicate that the universe is very likely flat.

Because inflation takes a small, homogenous region of the universe and expands the region exponentially until it becomes flat, it too predicts that the geometry of the universe should be flat. Recent experiments, including BOOMERanG, MAXIMA, and WMAP, have shown that fluctuations, which give the CMB its slightly imperfect uniformity, cluster around one degree in angular size, another trait that strongly suggests a flat universe.

/// ANDREI LINDE: VISIONS OF THE TRUTH

In 1981, when Andrei Linde learned of Alan Guth's seminal paper on inflation, it threw him into a funk. "Here was this brilliant idea that did not work," recalls Linde, who at the time was on the faculty of the Lebedev Physical Institute in Moscow. "After that, I spent quite a long time thinking about it, trying to come up with a solution."

Some months later, he got excited about an idea that potentially solved the problem that had stumped Guth. He decided to run the notion by a friend, whom he called late at night from his bathroom so as not to wake up his wife and two kids. Encouraged by his friend's reaction, he woke up his wife, physicist Renata Kallosh, to modestly state: "I know how the universe began." Thus was born new inflation — a concept independently developed by Paul Steinhardt and Andreas Albrecht in a paper that came out shortly after Linde's.

Although new inflation was widely considered the first viable inflation model, the reception was not uniformly enthusiastic. Linde presented his theory at an international conference in Moscow in October 1981 and felt that "many were excited by my paper." Stephen Hawking spoke the next day, with Linde serving as translator. Hawking discussed an "interesting suggestion" by Linde to improve Guth's original scenario, but said it was wrong. "For half an hour, I was translating in front of some of the top physicists in the world, explaining why my idea could not work," Linde says. "It was extremely embarrassing for a young physicist to be crushed by such a famous scientist in this way." Linde spoke with Hawking for several hours later that day and night, earning enough respect to be invited to a conference at Cambridge University the following summer.

In 1986, Linde fell into another funk, this one more severe than the last, largely because Soviet leader Mikhail Gorbachev had passed an edict prohibiting the nation's scholars from publishing their work abroad. Linde felt unmotivated until he received a call from his research institute asking him to give a series of lectures in Italy. He had less than a day to provide the text of those lectures. He racked his brains, trying to figure out something new to say. Within half an hour of frenzied thought, he came up with his theory of the "eternally self-reproducing universe." Inflation, he concluded, was a self-perpetuating process that continually churned out new universes — radically different from our own — thanks to subtle shifts in initial conditions. "For me, this was a big breakthrough, just like Alan's discovery of old inflation," Linde recalls. "At that moment, many pieces of the puzzle fell into place. It was like a vision of the truth." His depression, not surprisingly, abruptly ended.

He joined the staff of CERN, the nuclear laboratory in Geneva, Switzerland, from 1989 to 1990, with every intention of returning to the Soviet Union, where his parents lived. But he and Kallosh were soon offered faculty jobs by Stanford University. Kallosh asked a colleague whether Stanford was any good.

"It is a cultural desert," the colleague replied, "but many people would die for such an offer." Linde and Kallosh accepted the Stanford bid, and they moved to California in 1990. While inflation is central to Linde's work, he continues to look beyond. "Inflation is an important part of our history, but it is not the whole story," he says. "Although it shapes the universe and forms the galaxies, it doesn't tell us about the nature of dark matter or dark energy."

Physics is not the whole story either, he adds. "Maybe it can take us as far as science goes, but it is not the end of all knowledge." By combining physics, cosmology, philosophy, and theories of consciousness, Linde hopes to bring us closer to that elusive goal.

collection. If not, the higher-resolution Planck spacecraft (scheduled for launch in early 2007) will have an even better shot. "It may take a new satellite, but ultimately this job will get done because there's so much riding on this measurement," says University of Pennsylvania physicist Max Tegmark.

Detecting traces of primordial gravity waves could reveal the energy scale of inflation, which is equivalent to showing when — and at what temperature — expansion began. The shape of the gravity curve relates directly to the energy of the antigravity scalar field, which will tell researchers about the physics governing inflation. "These waves are the only pieces of evidence remaining from the early universe," says Tegmark. "Until somebody comes up with another idea, they're our only hope of measuring anything that tells us about this epoch."

But we won't have to wait a decade to learn anything new, he adds. "WMAP and the Sloan survey are already showing us how flat space is — so far in perfect agreement with inflation," says Tegmark. "The gravity waves could really nail it down, but if we don't find them, people will start to wonder."

What's the alternative?

If not inflation, what else can explain the riddles the theory was designed to address? In 2001, Steinhardt and collaborators offered a possible answer, the "ekpyrotic" scenario (see "The universe goes pyrotechnic?," page 39), which they say can resolve the same problems in a "conceptually different and observationally distinguishable way." This model suggests the expanding universe "was created from the collision of two three-dimensional worlds moving along a hidden extra dimension," explains Steinhardt. Although the idea sounds wacky, its predictions are straightforward: The gravity-wave signature in the microwave background should drop off sharply at long wavelengths. Inflation, by contrast, predicts a "scale-invariant" signature with roughly equal amplitude waves on all scales. "I still like inflation," Steinhardt adds. "It's a wonderful theory that may prove to be right. But as a scientist, I have to ask: 'Is there another way to do it?'"

It's good to have alternative models, says Guth, so long as they're reasonable, although he admits he'd be disappointed if the ekpyrotic picture proves correct. "But science has to go on and new ideas have to be tested," he says. "If inflation is eventually replaced by something completely different, it will have served a valuable purpose nevertheless," continues Guth. "By providing a framework for discussing properties of the early universe and by highlighting what needs to be explained, it has set the stage for what must follow."

Eternal inflation and the origins of the universe

In 1983, Alexander Vilenkin of Tufts University made the astonishing suggestion that almost all inflation models are "eternal" — once the process starts, it never ends. Inflation, according to this view, is like a chain reaction, stopping in one region of space only to start in another, ultimately spawning an infinite number of "pocket universes."

Vilenkin has continued to explore the implications of this idea, as have Andrei Linde of Stanford and Alan Guth of MIT. Linde, for example, views the universe as a "self-reproducing fractal. We live in just one of the bubbles that has properties conducive to life, while other bubbles may be entirely different from ours," Linde says. "They used to throw eggs at people who discussed the anthropic principle at conferences. With inflation, it is no longer metaphysics, but physics."

The idea of a process that spins off universes faster than dot-com companies in the late 1990s may sound farfetched. But to Guth, "it seems far more plausible that our universe was the result of mass reproduction rather than one created from a unique cosmic event."

Even if we accept the notion that, once started, inflation continues without end, that still leaves open the question of where the material that triggered inflation came from in the first place. "Inflation does not explain how the universe began, nor does it set out to do so," says Guth. "But it does provide a physical mechanism for taking a subatomic speck and producing a vast region of space-time filled with matter. So, in essence, inflation reduces the question of the universe's origin to the question of how we get that subatomic speck." Although that question will not be easy to answer, it is less daunting to think about.

/// PAUL STEINHARDT: DIVERSIFIED RESEARCH PAYS OFF

To hear Paul Steinhardt describe his approach to science, you might think he's a mutual fund manager. He follows a diversified strategy, making investments in many areas of research in the hopes that some will pay off big. There is, of course, an enormous, critical difference: Steinhardt is motivated by the thrill of discovery rather than the thrill of making money. "I like the feeling of knowing something before anyone else does, no matter what field it's in," explains the Princeton physicist.

Given his predilection for taking on multiple projects, a significant number of them could fail. But since there are no angry shareholders to answer to, he says, "You don't have to tell people about all your failures, just your successes." There have been many.

As an undergraduate, Steinhardt began working on condensed matter physics, studying the structure of glassy solids. This work eventually led him to discover a new class of matter called "quasi-crystals," in which atoms are packed quasi-periodically (rather than periodically as in crystals), thereby making unusual symmetries possible. He continues to study the properties of these novel materials when he's not doing cosmology.

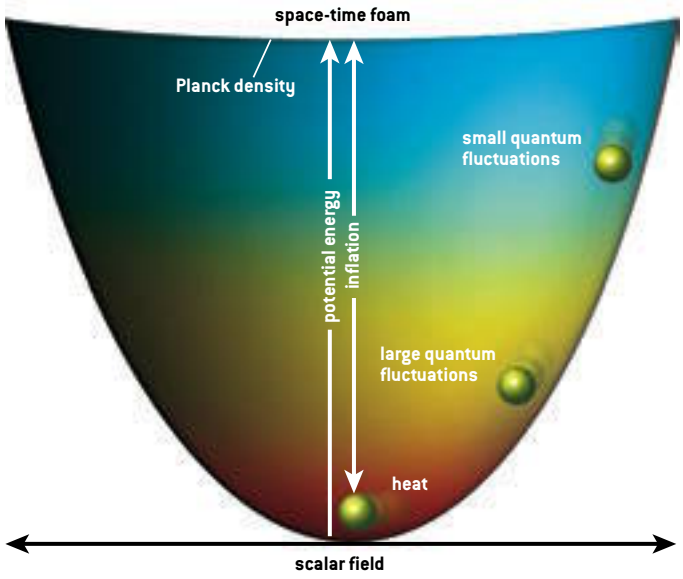
Steinhardt's work in cosmology began in 1980, when he was a graduate student at Harvard and heard Alan Guth's first talk at the university about inflation. "His lecture built up to a climax and ended in disaster, as his model produced a universe that looked nothing like the one we see," Steinhardt says. "I soon started working on ways to solve that problem, following lots of twists and turns that ended up as new inflation. But I had a lot to learn because I knew nothing about cosmology at the time."

New inflation grew out of his background in condensed matter physics, where phase transitions rule the game. "The phase transition in Alan's model got stuck, and he didn't know how to complete it," Steinhardt says. "I realized that things might work better with a different type of phase transition."

Steinhardt has developed other inflationary models since new inflation, but these days he's more involved in studying dark matter, dark energy, and cosmic acceleration. He coined the term "quintessence" and coauthored the first paper on the subject, after concluding squarely that the energy driving the universe's acceleration might vary over time rather than be a "cosmological constant" as Einstein once posited.

"The idea of quintessence, at its simplest form, is really just inflation at a much lower energy scale." With Princeton colleague David Spergel, Steinhardt is currently exploring the possibility that dark matter is strongly rather than weakly interacting — SIMPs as opposed to WIMPs — to account for the fact that matter does not clump on small scales to the extent predicted in most dark matter models. "The dark side of the universe may be far more complicated than we imagine," Steinhardt says. "Look at how complex the 4 percent we know of is — dust, gas, and other matter. Why should the other 96 percent be simple?"

Meanwhile, this inflation pioneer is now one of the prime movers behind inflation's biggest rival at present, the ekpyrotic scenario. "My hope is not to kill inflation, but to create a possible contender," Steinhardt explains. "There's a tendency to assume a model is correct because it's the only one standing. The best part about having an alternative is that it opens your mind up."



Is inflation supernatural?

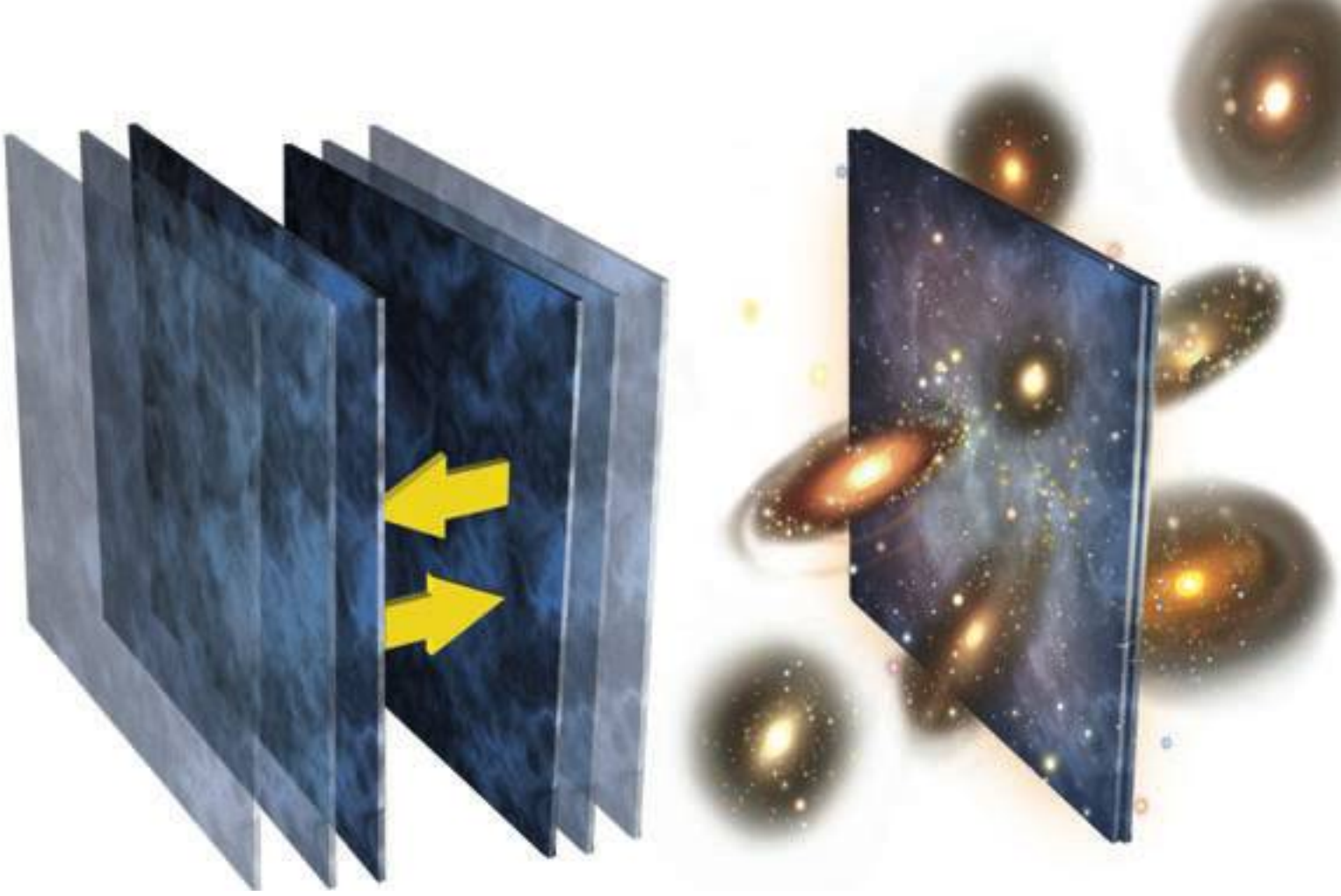
What if inflation is driven by two scalar fields instead of just one, as is typical in most cosmological models? The idea makes sense to Harvard physicist Lisa Randall, who says scalar fields often operate in concert. "Previous inflationary models don't do a good job of ending inflation," Randall says. "The main thing lacking was a switching mechanism. The idea of having a separate field to turn off inflation seems like a dramatic improvement."

Randall and Marin Soljacic, an MIT graduate student at the time, teamed up with Alan Guth, MIT's resident inflation expert, to devise their so-called supernatural model. One field in this model provides the bulk of the energy density needed to drive inflation, while the second field acts as a trigger to turn it off. "We think it works like a seesaw," Guth explains.

"The energy field holds down one end, while the second field presses on the other end with increasing force, as if sand were being dropped on it. Eventually, the whole thing tips over and inflation ends."

Guth acknowledges that in reality there may be even more than two scalar fields at play. "Supersymmetry models usually have a large number of scalar fields," Guth says. "In that case, supernatural inflation might be an improvement over the status quo, but still an oversimplification."

One way to find out if the model is right is to look for a sharp peak at short wavelengths in the spectrum of the universe's microwave background radiation. For technical reasons, that peak will be hard to detect. But supernatural inflation predicts the creation of primordial black holes in the early universe, long before other structures formed. Studies that indicate galaxy formation was "seeded" by primordial black holes — a notion yet to be confirmed — might provide support for the supernatural model before the exacting microwave measurements are complete.



The universe goes pyrotechnic?

In March 2001, Justin Khoury and Paul Steinhardt of Princeton University, along with Neil Turok of Cambridge University and Burt Ovrut of the University of Pennsylvania, unveiled a potentially serious alternative to inflation. Their "ekpyrotic model," derived from the Greek term *ekpyrosis* meaning conflagration is based on M-theory — the latest, most fundamental version of string theory. According to M-theorists, our universe might lie on a three-dimensional sheet-like membrane, or "brane," which floats in a hidden fifth dimension (the fourth dimension being time). The theory also posits the existence of six higher spatial dimensions, all tied up in extremely tiny circles much smaller than the radius of a proton.

In the ekpyrotic scheme, the driving force behind the universe's expansion comes not from inflation but from a collision between our universe and another parallel "brane" universe arriving from a higher dimension. This scenario does not contradict the idea of a universe that has expanded and cooled since the Big Bang. Instead, says Steinhardt, the model amends the earliest moments of the story, offering a different explanation for what put the "bang" in the Big Bang.

About a week after the Khoury paper was posted, Andrei Linde and his wife, Renata Kallosh, both at Stanford, along with Lev Kofman of the University of Toronto challenged the model in a 21-page critique. The model works better, they say, by simply changing the sign of one parameter. They call their "improved scenario" the "pyrotechnic universe," while acknowledging it still suffers from problems that beset the original theory.

Steinhardt is unconvinced by Linde's arguments. "This is a whole different approach, rather than a specific model," he says. It's worthwhile, in any case, to try to devise alternative approaches, he adds. "Either we'll learn that this is a viable alternative or that it's hard to come up with an alternative to inflation."

/// ALEXANDER VILENKIN: COSMOLOGIST AGAINST ALL ODDS

After reading a text on general relativity in high school, Alexander Vilenkin knew he wanted to become a cosmologist. But despite an obvious talent for physics, Vilenkin could not get into a graduate physics program after finishing college, nor could he find other employment in the field, primarily because he was a Jew living in the Soviet Union in the 1970s. Instead, he was forced to take a succession of mundane jobs in his hometown of Kharkov, Ukraine. For over a year, he worked as a night watchman at a kiosk that sold alcohol, and then at a zoo, studying physics whenever he could. He taught at an evening school where many students failed to show up because of drinking problems. It was his responsibility "to go to their houses and drag them there."

Unable to pursue physics and disenchanted with the Soviet system, Vilenkin got permission to leave the country with his wife in 1976. They spent several months in Italy waiting for their U.S. visas. While in Italy, Vilenkin applied to graduate school at the State University of New York in Buffalo, where a friend of his had just been accepted. Vilenkin also was accepted, and he started his graduate work in physics in September. He earned his Ph.D. the following spring.

His dissertation work was in the field of biopolymers, he explains, "because everyone told me I would never get a job in cosmology." But he thought about cosmology constantly and even published a paper on black holes that year. In 1977, he accepted a post-doctoral position at Case Western Reserve in Cleveland, Ohio, in ferro-electricity, the physics of metals, but also continued his work on black holes. A year later, he joined the faculty of Tufts University in Medford, Massachusetts, ostensibly to work in condensed matter physics. He switched to cosmology right away, fulfilling a longstanding dream.

"I got lucky several times in a row," claims Vilenkin, although skill was clearly involved as well. "It was hard to get a job in physics at the time, and Buffalo was not the world's most famous school. It was especially unlikely that someone like me would get a job with a Ph.D. in biopolymers from Buffalo without any backing from my adviser."

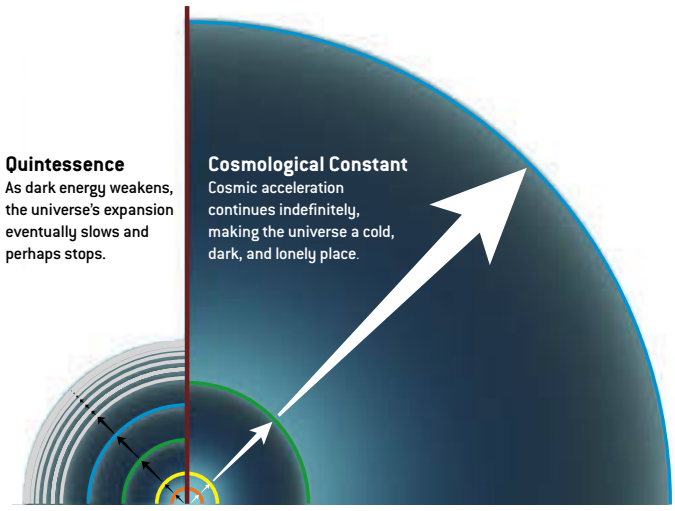
Nevertheless, Vilenkin has taken full advantage of his opportunity, remaining at Tufts ever since. In 1982, he published a paper on inflation and quantum cosmology, explaining how the universe could be created from nothing. "Quantum cosmology was not really a field at the time — and for good reason," he says. "If you imagine a universe created spontaneously, it would be very small and nobody knew how to make it large. Inflation provides the mechanism."

In another paper the following year, Vilenkin argued that inflation is eternal — once started, it continues without end. He's now trying to determine whether inflation is eternal in the past, as well as into the future, which would mean the universe would not have a beginning.

Vilenkin was also a leading developer of the concept of cosmic strings — dense, linear "defects" in the fabric of space that formed during phase transitions in the early universe. The idea that these strings might act as seeds for galaxy formation was ruled out by recent microwave background observations, he says. But he does think that defects like strings exist and, if found, could teach us some interesting physics.

His work is not driven by a particular goal, Vilenkin says, "but there are some very puzzling questions that I'd very much like to understand. It's a pleasure to think about them, and there's always the hope that I might come up with an idea that provides some answers."

In a recent paper, Vilenkin and a Spanish colleague, Jauma Garriga, argued that there are an infinite number of regions of space the same size as our observable universe, but that the number of "histories" — or things that could possibly happen within these realms — is finite. "The same conversation we are now having could be happening in a number of regions," he said in an interview. "So there are regions in which I'm a tenured physics professor and others in which I'm still guarding the zoo."


Quintessence
As dark energy weakens, the universe's expansion eventually slows and perhaps stops.
Cosmological Constant
Cosmic acceleration continues indefinitely, making the universe a cold, dark, and lonely place.

Quintessential inflation

Cosmologists now believe that nearly three fourths of the stuff that makes up the universe consists of mysterious "dark energy" — not to be confused with the equally puzzling, though less abundant, dark matter. A prime candidate for this dark energy, which pushes the universe apart ever faster, is called the cosmological constant — the energy of the vacuum. The leading alternative is a hypothetical form of matter that permeates all space dubbed quintessence.

Like inflation, quintessence is thought to have originated when the universe was just 10^{-35} second old. And it is also driven by a scalar field whose energy varies. The resemblance is not coincidental, according to Princeton's Paul Steinhardt, because the idea was modeled after inflation. The big difference is the energy and time scale: Inflation occurred quickly at very high energies, whereas the scalar field responsible for quintessence operates at much lower energies over a much longer time frame. "It looks like the universe is sandwiched between two periods of cosmic acceleration," says Steinhardt.

"The currently observed acceleration of the universe — if it's real, and it certainly appears to be real — provides direct evidence that gravity can act repulsively," says MIT's Alan Guth. "That gives us more confidence that inflation is right."

But some believe there may be an even stronger link between inflation and quintessence. In 1999, Alexander Vilenkin of Tufts University and James Peebles of Princeton proposed that the same scalar field could drive both inflation and quintessence. The premise of this model is that the field responsible for inflation operates in a high-energy regime, but its intensity drops off quickly, and its effects — masked by other more energetic phenomena — do not become apparent until much later in the universe's history. "I'm not ready to say that this is better than other models, but at least it's a testable scenario," Vilenkin notes.

The search for a final theory

Quantum field theory, upon which inflation now rests, may not be adequate to explain the universe's sudden expansion, says MIT's Alan Guth. Instead, we may need a theory of so-called "quantum gravity" to really understand the mechanism driving inflation. Quantum gravity, which is still in its formative stages, is an attempt to develop a "theory of everything" — one theory that unites the intricacies of quantum mechanics with the force of gravity as described by Einstein's general relativity. The underlying hope is to combine the strengths of both particle physics and cosmology into a single, powerful tool.

String theory, which describes a universe with as many as 11 dimensions, represents one approach to establishing a quantum gravity theory. Ultimately, says Guth, we may have to describe inflation in terms of strings.

"At the moment, there's a large variety of string-theory models, which is a sign we don't know enough to converge on any one soon," says Alexander Vilenkin of Tufts University. "The same holds for inflationary models, and I think the two things are connected. If we're lucky, one day we'll converge on a unique theory, but I don't see that happening anytime soon."

Can scientists' "theory of everything" really explain all the weirdness the universe displays? /// BY EDWARD WITTEN

Astronomers have wrapped up cosmic history in a neat package. Or so it might seem. Some 12 to 14 billion years ago, the universe came into existence — along with space and time themselves. A fraction of a microsecond later, inflation set in, and for a brief period, the cosmos expanded at an explosive rate. Within a billion years, galaxies began to form with the aid of dark matter, which still holds them together. And now, a mysterious force known as dark energy seems to be taking over, accelerating the universe's ongoing expansion.

Yet this picture just skims the surface. Scientists aim to dig deeper, to understand why things happened the way they did. What was the Big Bang, and how could time just begin? What caused cosmic inflation? And what, exactly, are dark matter and dark energy?

Many scientists believe the answers to these questions are tied up with some of the deepest unsolved problems in physics. A thirty-year-old framework known as string theory promises new insights and offers hope that answers to at least some of these puzzles may be on the horizon.

The story begins early in the 20th century, when Albert Einstein drastically changed our notions about space and time. In Einstein's theory, space and time, which in everyday experience seem completely different, were unified into a strange new concept that came to be called space-time. His ideas have held up well — almost everything else in our fundamental description of physics has changed since Einstein's day, but we still describe space-time using the concepts he introduced. Yet many scientists suspect this is destined to change and that new developments in the understanding of space-time will need to emerge before we can attack the grand puzzles ahead.

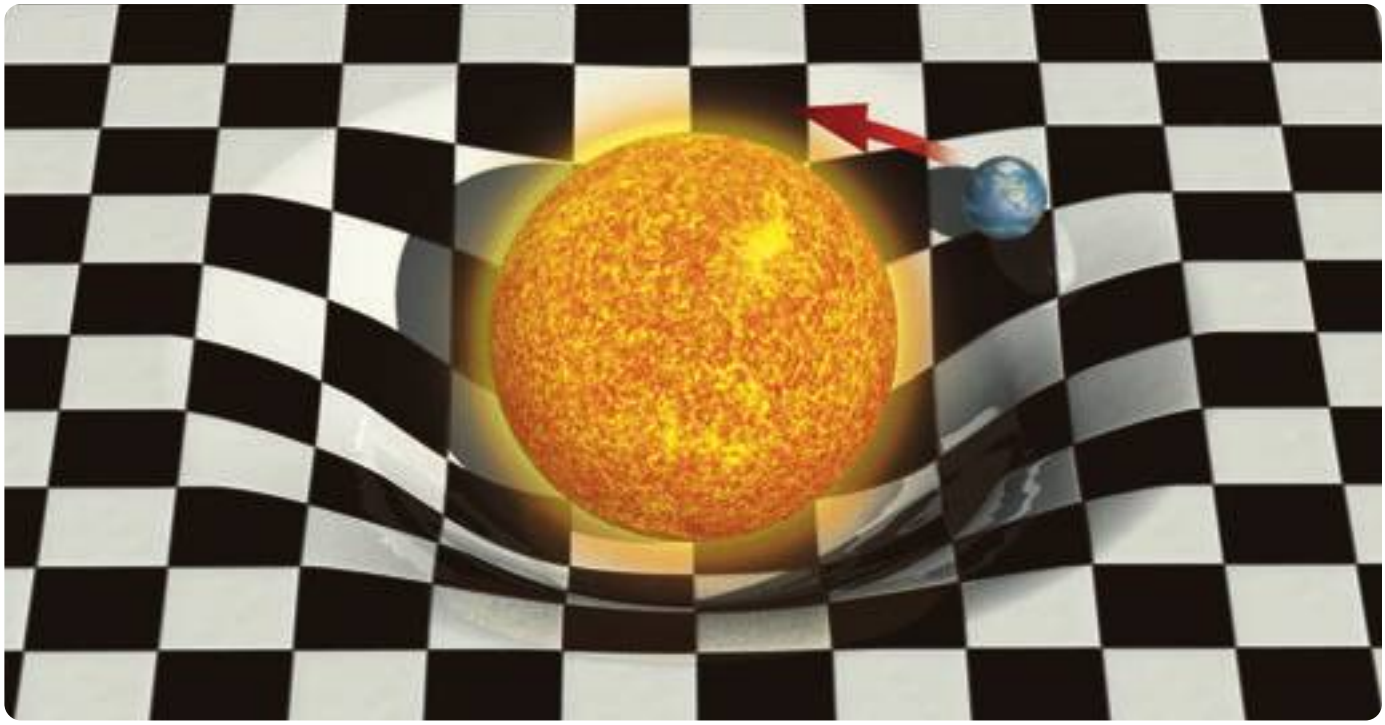
Actually, Einstein transformed our concepts of space and time with two startling revelations. The first upheaval came in 1905 with the theory of special relativity, which explored the strange behavior of matter moving near the speed of light. The theory showed how clocks carried on a rapidly moving spaceship slow down and the heartbeat of an astronaut almost stands still — as seen by an observer at rest.

Updated from the June 2002 issue of *Astronomy*

Universe

STRING THEORY suggests that particles in the universe are composed of loops of vibrating strings. Like a violin or piano string, one of these fundamental strings has many different harmonics. In string theory, harmonics correspond to different elementary particles. If string theory proves correct, electrons, photons, and neutrinos are different due to changes in the vibrations of the strings. ILLUSTRATION: *ASTRONOMY*: CHUCK BRAASCH

on a string



ACCORDING TO EINSTEIN, gravity arises because massive objects, like the Sun, warp space-time, causing smaller objects like Earth to orbit them.

ASTRONOMY: ROEN KELLY

Ten years later, when most scientists had barely recovered from the first shock, the second revolution arrived. In 1915, Einstein completed his greatest and most surprising achievement: the theory of gravity known as general relativity. According to general relativity, space-time is curved, and the curvature is created by matter. When planets travel in elliptical orbits around the Sun, for example, they are merely seeking the most direct paths in the curved geometry created by the Sun's gravity.

Surprising predictions from special relativity ranged from an ultimate speed limit — nothing can travel faster than the speed of light — to the famous formula, $E=mc^2$, that describes the equivalence of mass and energy. General relativity, on the other hand, predicted gravitational waves, black holes, the bending of light by the Sun, and the expansion of the universe.

After Einstein, further discoveries changed almost everything else in our understanding of physics. Scientists discovered new building blocks of matter and the surprising laws that govern their behavior. But all the new phenomena occurred, and all the new particles were found, in the space-time arena that Einstein had set forth.

In the 1920s, we learned that subatomic particles obey not Newton's laws of motion but the weird and wonderful laws of quantum mechanics, in which particles behave as waves and Heisenberg's uncertainty principle (you can know an electron's velocity or its position, but not both) gives everything a fuzziness nearly impossible to describe in words. By the mid-1970s, quantum theory was expanded into a theory of elementary particles — the standard model of particle physics — which in its own realm is every bit as successful as Einstein's theory.

By the 1970s, a clear division of labor existed in our understanding of physics. General relativity described large objects such as the solar system, galaxies, and the universe. Quantum mechanics, as elaborated in the standard model, described small objects such as atoms, molecules, and subatomic particles.

Physicists, however, are not satisfied having two different theories that work in two different realms. One reason is simply that big objects ultimately are made out of little objects. The same forces operate on both atoms and stars, for example, even though gravity is more obvious for stars while electricity and magnetism dominate in atoms. So it must be possible to combine the standard model and general relativity into a bigger, more complete theory that describes the behavior of both atoms and stars.

Moreover, the quest for unification has paid enormous dividends in the past. Both the standard model and general relativity were discovered, in large part, through efforts to unify earlier theories. Unfortunately, direct attempts to express general relativity in quantum mechanical terms have led to a web of contradictions, basically because the nonlinear mathematics Einstein used to describe the curvature of space-time clashes with the delicate requirements of quantum mechanics.

String theory to the rescue?

Occasionally, when scientists face a big problem like this one, someone disappears into an attic for seven years and emerges with an answer. That, more or less, is how Andrew Wiles proved Fermat's Last Theorem. In the case of quantum gravity, the "scientist in an attic" approach has never borne much fruit. Luck played a role instead: Physicists who originally had quite a different goal in mind stumbled onto a promising approach.

This came about in the early 1970s with the development of string theory. According to string theory, an elementary particle is not a point but a loop of vibrating string. Just like a violin or piano string, one of these "fundamental strings" has many different harmonics or forms of vibration. For a piano string, the

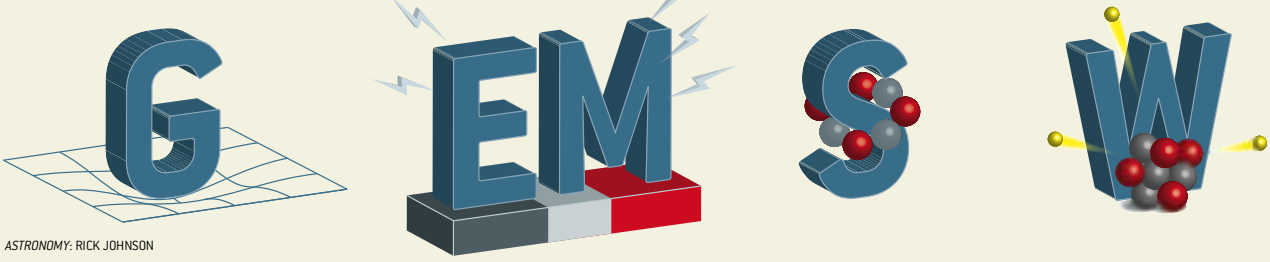
Edward Witten *is a professor of physics at the Institute for Advanced Study in Princeton, New Jersey.*

GRAVITY describes the attractive force of matter. It is the same force that holds planets and moons in their orbits and keeps our feet on the ground. It is the weakest force of the four by many orders of magnitude.

ELECTROMAGNETISM describes how electricity and magnetic fields work. It also makes objects solid. Once believed to be two separate forces, it was discovered both could be described by a simple set of equations.

THE STRONG NUCLEAR FORCE is responsible for holding the nucleus of atoms together. Without this force, protons would repel one another so no elements other than hydrogen — which has only one proton — would be able to form.

THE WEAK NUCLEAR FORCE explains beta decay and the associated radioactivity. It also describes how elementary particles can change into other particles with different energies and masses.



ASTRONOMY: RICK JOHNSON

The equations that describe gravity, including Einstein's theory of general relativity, predict the behavior of objects on macroscopic scales extremely accurately. In the microscopic world, however, electromagnetism, the strong nuclear force, and the weak nuclear force dominate. Collectively, they provide the foundation of quantum mechanics. Because gravity is so weak at small scales compared to the other forces, particle physicists don't even bother to account for it in their experiments. To illustrate this, imagine a single proton lying on the floor and another suspended one yard (meter) above it. The strong nuclear force is so powerful that the top proton's attraction easily outmuscles the gravitational pull of the entire Earth.

Why try to unite the four forces in a single theory? Why not simply use Einstein's theory of general relativity to govern big things and quantum mechanics for little ones? Some concepts, such as the Big Bang or how black holes form, live in both domains. When we combine equations of the four forces to describe these ideas, our answers usually end up being either zero or infinity. Neither answer is worse; describing an object bigger than the (finite) universe — or one that doesn't exist — are both equally impossible.

Here's where string theory comes to the rescue. By adding seven hidden dimensions to the familiar three and another for time, plus antiparticles and a mirror set of particles called superparticles, the math starts to make sense. The force of gravity is diluted because it permeates into one or more of the hidden dimensions. Dark matter and dark energy also may invisibly shape our universe from these phantom dimensions.

So how do we know if string theory is real or just a mathematical abstraction? At this point, no one has devised an experiment that can prove or disprove it. Critics say there will never be such an experiment. Proponents, however, see such beauty and symmetry in the equations — as nature has revealed so often in the past — that it would be tragic if some form of string theory was not real. — *Tom Ford*

harmonics consist of a basic note — such as middle C — and its higher overtones (one, two, or several octaves higher). The richness of music comes from the interplay of higher harmonics. Music played with a tuning fork, which produces only a basic note, sounds harsh to the human ear.

In string theory, different harmonics correspond to different elementary particles. If string theory proves correct, all elementary particles — electrons, photons, neutrinos, quarks, and the rest — owe their existence to subtle differences in the vibrations of strings. The theory offers a way to unite disparate particles because they are, in essence, different manifestations of the same basic string.

How does this help us with gravity? In the early 1970s, calculations showed that one of the string's vibrational forms had just the right properties to be a graviton, the basic quantum unit of gravity. Curiously, like many of the most important discoveries in string theory, this one came about when a researcher made a technical calculation without realizing, at the time, the full implications of his work.

From little acorns grow mighty oaks. A quantum theory with gravitons must, according to arguments that physicists have known for years, incorporate the full structure of Einstein's theory — at least in circumstances involving astronomical bodies where general relativity successfully applies. (At the atomic level, such a theory has to depart from Einstein's, which doesn't work quantum mechanically.)

Back in the early 1970s, one of the pioneers of string theory, Italian physicist Daniele Amati, characterized the theory as "part of 21st-century physics that fell by chance into the 20th century." He meant that string theory had been invented by chance and developed by a process of tinkering, without physicists really grasping what was behind it. Amati surmised that a true understanding of the foundation of this remarkably rich theory would have to await the 21st century.

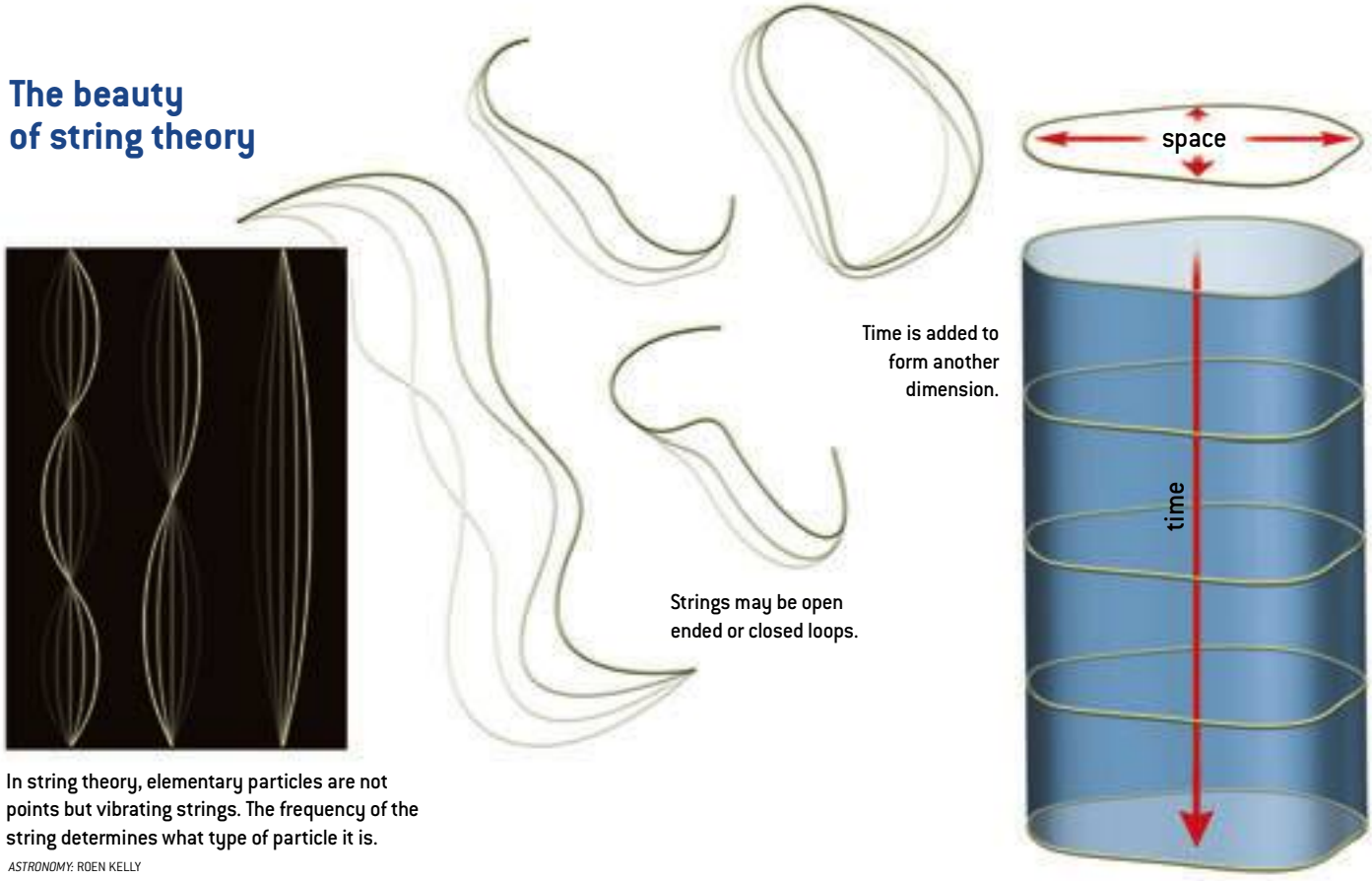
Thirty years later, we have a firmer grip on many issues, yet there's still much we don't understand at all — including the foundations of string theory. On the other hand, with the 21st century only just begun, we have yet to fall behind Amati's schedule!

The fuzziness of space-time

Perhaps the most basic thing we have learned about string theory is that it modifies the concepts of space-time that Einstein developed. This doesn't come as a complete surprise: Einstein based his theory of gravity on his ideas about space-time, so any theory that modifies Einstein's gravitational theory to reconcile it with quantum mechanics has to incorporate a new concept of space-time.

String theory actually imparts a "fuzziness" to all our familiar notions of space and time, just as Heisenberg's uncertainty principle imparts a basic fuzziness to classical ideas about the motion of particles. In ordinary quantum mechanics, interactions among elementary particles occur at definite points in space-time. In

The beauty of string theory



In string theory, elementary particles are not points but vibrating strings. The frequency of the string determines what type of particle it is.

ASTRONOMY: ROEN KELLY

string theory, things are different: Strings can interact just as particles do, but you cannot say quite when and where this occurs.

Even to a theoretical physicist, this kind of explanation raises more questions than it answers. String theory involves a conceptual jump that's large even compared with previous revolutions in physics. And there's no telling when humans will succeed in crossing the chasm.

Nevertheless, we really do understand one aspect of how string theory changes our notions of space-time. This involves a key part of string theory called supersymmetry. Finding supersymmetry offers cosmologists' best and brightest hope of proving that string theory has something to do with nature and is not just armchair theorizing.

In our everyday life, we measure space and time by numbers. For example, we say, "It is now 3 o'clock," "We are 200 feet above sea level," or "We live at 40° north latitude." This idea of measuring space and time by numbers is one bit of common sense that Einstein preserved. In fact, in his day, quantities that could be measured by numbers were all physicists knew about.

But quantum mechanics changed that. Particles were divided into bosons (like light waves) and fermions (like electrons or neutrinos). Quantities like space, time, and electric field that can be measured by numbers are "bosonic." Quantum mechanics also introduced a new kind of "fermionic" variable that cannot be measured by ordinary numbers. Fermionic variables are infinitesimal and inherently quantum mechanical, and as such are hard to visualize.

According to the idea of supersymmetry, in addition to the ordinary, familiar dimensions — the three spatial dimensions plus time — space-time also has infinitesimal or fermionic dimensions. If supersymmetry can be confirmed in nature, this will begin the process of incorporating quantum mechanical ideas into our description of space-time. But how can we ever know if supersymmetry is right?

Discovering supersymmetry

In a world based on supersymmetry, when a particle moves in space, it also can vibrate in the new fermionic dimensions. This new kind of vibration produces a cousin or "superpartner" for every elementary particle that has the same electric charge but differs in other properties such as spin. Supersymmetric theories make detailed predictions about how superpartners will behave. To confirm supersymmetry, scientists would like to produce and study the new supersymmetric particles. The crucial step is building a particle accelerator that achieves high enough energies.

At present, the highest-energy particle accelerator is the Tevatron at Fermilab near Chicago. There, protons and antiprotons collide with an energy nearly 2,000 times the rest energy of an individual proton. (The rest energy is given by Einstein's well-known formula $E=mc^2$.) Earlier in this decade, physicists capitalized on Tevatron's unsurpassed energy in their discovery of the top quark, the heaviest known elementary particle. After a shutdown of several years, the Tevatron resumed operation in 2001 with even more intense particle beams.

In 2007, the available energies will make a quantum jump when the European Laboratory for Particle Physics, or CERN (located near Geneva, Switzerland) turns on the Large Hadron Collider, or LHC. The LHC should reach energies 15,000 times the proton rest energy. The LHC is a multi-billion dollar international project, funded mainly by European countries with substantial contributions from the United States, Japan, and other countries.

If our hunches prove correct, there's an excellent chance that supersymmetry lies within reach of the LHC, and maybe even of

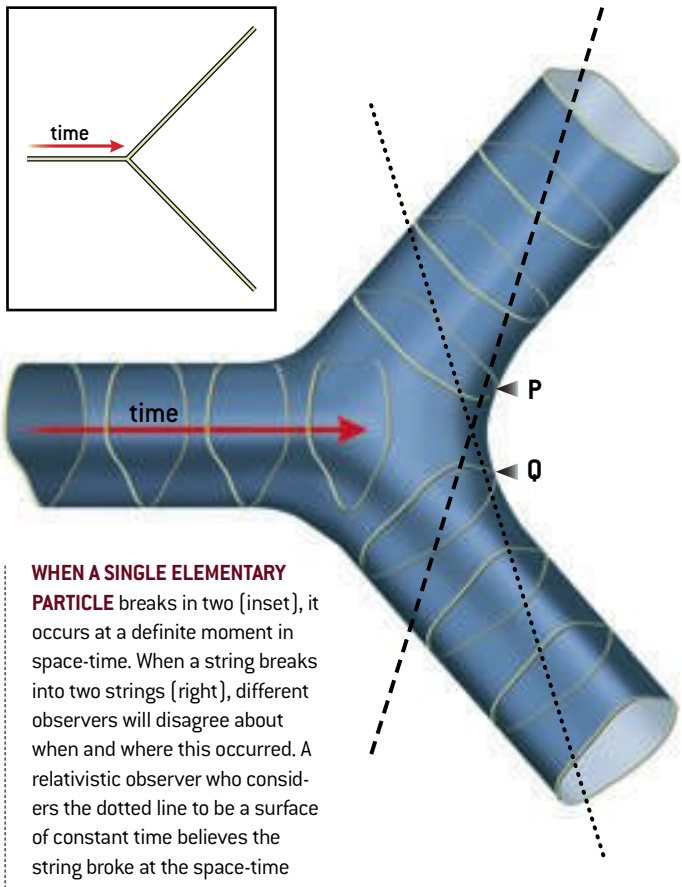
the Tevatron. Many physicists suspect the LHC will produce supersymmetric particles at a huge rate. If that happens, elementary particle physics will enter a completely new era, with the experimental study of phenomena derived from the quantum structure of space-time. The next step would be to study supersymmetric particles in detail and extract crucial clues that could help us understand string theory or whatever deeper theory underlies supersymmetry.

The Tevatron and the LHC accelerate protons — and, in the case of the Tevatron, antiprotons also. Proton accelerators afford the easiest way of reaching the highest possible energy because protons can be accelerated much more easily than other particles.

Unfortunately, proton accelerators have a drawback. They typically produce dozens of uninteresting particles along with the particles of interest. The supersymmetric world is far too complicated to be explored fully at a proton accelerator. For accurate measurements, we need a different kind of machine — one that accelerates electrons and their antiparticles, positrons.

The highest-energy electron accelerators built so far have been at CERN and at the Stanford Linear Accelerator Center in California. These machines have carried out the most precise and complete tests of the standard model of particle physics. In the last decade, the United States, Japan, and Germany have devoted intensive research and development toward a higher-energy electron accelerator known as the Linear Collider, which could reach the energy level needed to study supersymmetric particles.

The yet-to-be-approved Linear Collider, like the LHC, will be a multi-billion dollar project that can be built only with extensive international cooperation — perhaps encouraged by the curiosity of the public in the countries involved.



WHEN A SINGLE ELEMENTARY PARTICLE breaks in two (inset), it occurs at a definite moment in space-time. When a string breaks into two strings (right), different observers will disagree about when and where this occurred. A relativistic observer who considers the dotted line to be a surface of constant time believes the string broke at the space-time point P while another observer who considers the dashed line to be a surface of constant time believes the string broke at Q. *ASTRONOMY:* ROEN KELLY

The astronomy connection

What about those astronomical mysteries we started with? None of the problems yet has any definitive solution, but physicists suspect solutions are linked to the exploration of supersymmetry, string theory, and the quantum nature of space-time.

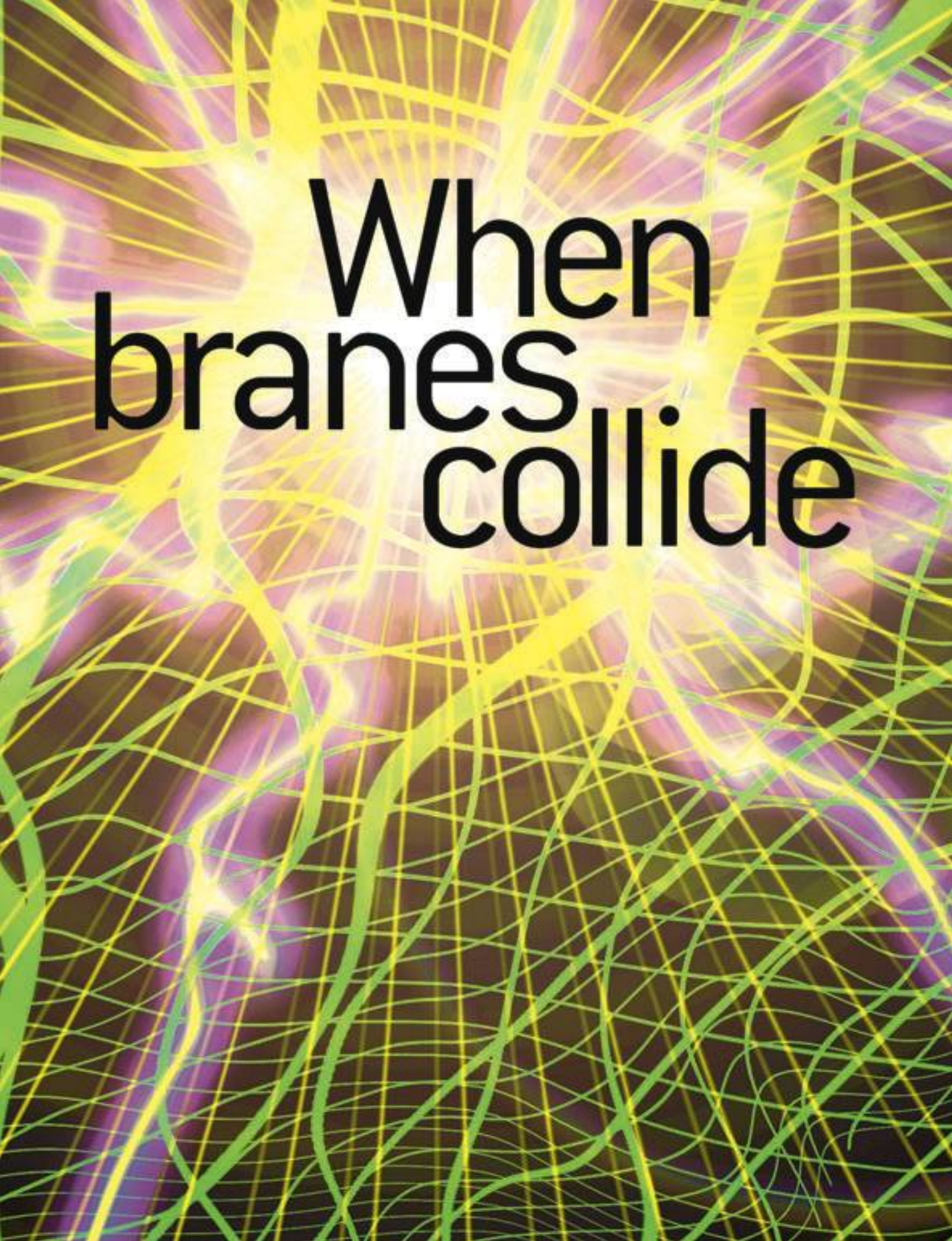
First, although other possibilities exist, many physicists think galactic dark matter is a cloud of supersymmetric particles gravitationally bound to a galaxy. Calculations show that such a cloud would have just about the right properties. If this supposition proves correct, dark matter will be detected in the next decade. Special underground detectors can spot the rare interactions of dark matter particles passing through Earth. The instruments lie deep underground, often in mines, to screen them from cosmic rays.

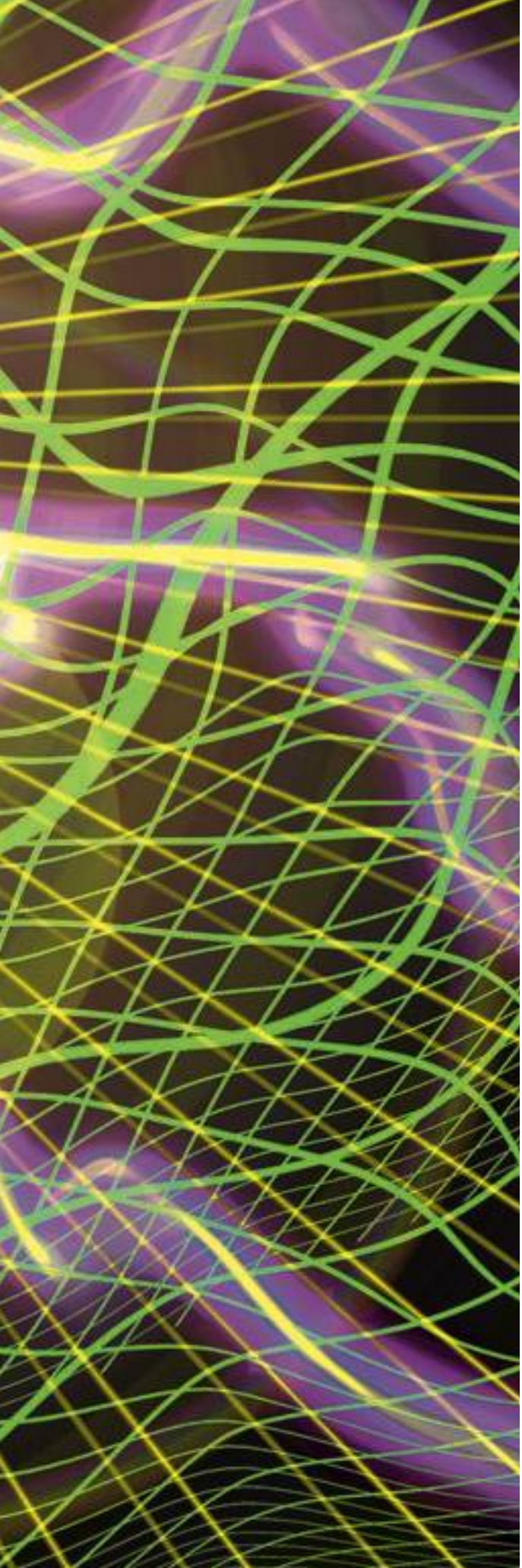
Detecting dark matter would be a milestone in astronomy, but not the whole story. Underground detectors would measure the product of the density of dark matter particles times the interaction rate, but that's only a partial solution. To learn how much dark matter of this type exists, scientists would need to measure the interaction rate by producing dark matter particles in accelerators and observing their properties. Thus, the LHC and the Linear Collider, together with supersymmetry, might be key to understanding dark matter.

The dark energy problem is a more difficult challenge. One of the most dramatic discoveries in astronomy and physics in recent years is that the expansion of the universe seems to be accelerating. This points to a tiny but positive energy density of the vacuum (or possibly a more complicated scenario involving another form of dark energy). The vacuum energy is a problem that involves both quantum mechanics, because this energy comes from quantum fluctuations, and gravity, because gravity is the only force in nature that "sees" the energy of the vacuum. Because string theory is the only framework we have for understanding quantum gravity, the vacuum energy poses a problem for string theorists that remains to be solved.

As for inflation, scientists believe it occurred in the early universe at a temperature far above the energy attainable with particle accelerators and relatively close to the energy at which quantum gravity becomes important. We do not yet have a convincing model of how and why inflation transpired because our current models of particle physics are not adequate at the enormous energy levels of inflation. Understanding inflation requires a much better grasp of particle physics than we now have, and possibly a full knowledge of string theory and quantum gravity.

Finally, what was the Big Bang all about, and how could there have been a beginning to space and time? This question certainly involves quantum gravity, because quantum mechanics and general relativity were both important near the Big Bang. That creates another grand challenge for string theorists, even though we do not seem close to an answer. A plausible guess springs from the way quantum gravity and string theory impart a fuzziness to our concepts of space-time. Under ordinary conditions, time seems like a well-defined notion, but as you get closer to the Big Bang, quantum mechanical and stringy fuzziness become more significant. The very notion of time may lose its meaning when one gets back to the beginning — and that, quite likely, will prove to be a key to understanding what the Big Bang really was.


When
branes
collide



Can a few extra dimensions solve the riddles of the universe? Or will they usher in a whole new set of cosmic mysteries? /// BY STEVE NADIS

Near the end of the nineteenth century, many physicists believed there wasn't much left to do apart from tidying up a few loose ends in the prevailing theories of the day. As it turned out, those "loose ends" would haunt the minds of the greatest thinkers for the next several decades and eventually spawn the new physics of quantum mechanics and general relativity, which dominate the field today. Now, at the start of the 21st century, physicists again find themselves at a familiar crossroads in their effort to wrap the universe into a neat, manageable parcel governed by a handful of elegant equations.

As it was nearly a century ago, fresh ideas are being born from this search for the "theory of everything." But this time, physicists are looking to higher dimensions for answers. And there are preliminary indications, at least on the theoretical front, that they may be on the right track after all.

In the realm of human experience, four dimensions (three spatial and one temporal) adequately describe reality. But what if there were, say, six more spatial dimensions hidden from our worldly view? What if one of these extra dimensions was so large that it contained the entire visible universe, while the other five were wrapped up so small that they couldn't be seen at all? According to M-theory, a leading contender for the title of ultimate theory, this seemingly implausible picture may, in fact, be correct.

As it currently stands, M-theory is the latest, most fundamental version of string theory — a construct that holds that elementary particles (and, by extension, the entire universe) can be described by wave-like vibrations of fundamental entities called strings. As a matter of fact, M-theory unites five previously disparate versions of string theory into one coherent package.

Updated from the May 2002 issue of *Astronomy*

TWO BRANES COLLIDE (green grids), and our universe (yellow grid) evolves on one of them. This process may be cyclical, happening an infinite amount of times, or may occur only once. *ASTRONOMY:* TOM FORD

According to M-theorists, our universe lies on a three-dimensional membrane, or "brane," that floats in a fifth dimension (with the fourth dimension being time). The theory also posits the existence of five higher spatial dimensions, which generally can be ignored because they are wrapped up in tiny circles far smaller than the radius of a single proton (see "Extra dimensions: Where are they?," page 52). As weird as these ideas may sound, several physicists have found success recently in applying M-theory to a host of cosmological questions.

Extra dimensions?

University of Chicago cosmologist Michael Turner, for one, is intrigued by the possibility that the solutions to several cosmic conundrums may stem from the interactions of branes in higher dimensions. So far, conventional physics has been unable to tell us what the Big Bang really was, what caused it, or why the expansion of the universe is accelerating, Turner says. "The Big Bang theory has been incredibly successful, but it's really only a theory of what happened after the Big Bang." Moreover, the dark energy associated with cosmic acceleration, which is thought to comprise the bulk of energy in the universe, is equally mystifying. "Getting to the bottom of these mysteries with extra dimensions may sound like a stretch," he says, "but we need crazy ideas to get to the bottom of this."

> "It doesn't take a genius to say that all of the ideas out there are wrong – or incomplete at best." – Michael Turner

Already, a handful of scientists have started putting M-theory to work on the most pressing of these problems. Princeton University physicist Paul Steinhardt — an early proponent of cosmic inflation, which purports that the universe suddenly underwent a smoothing period of rapid expansion a tiny fraction of a second after the Big Bang — is now drawing on M-theory to offer an alternative to inflation. In addition, Steinhardt and his colleagues, Justin Khoury of Princeton University, Burt Ovrut of the University of Pennsylvania, and Neil Turok of Cambridge University, have offered an explanation for what caused the Big Bang and what came before. According to their model — presented in March 2001 and dubbed the ekpyrotic scenario after the Greek word *ekpyrosis* meaning conflagration — the Big Bang could have been the by-product of a fiery collision between two flat and parallel branes drifting through the fifth dimension (see opposite page).

In principle, there's no restriction against the universe emerging from such a megadimensional head-on collision. Sufficient energy and heat would be generated in such an event to fuel the observed expansion of the universe without inflation. And the temperature and density fluctuations that astronomers see today could be attributed to quantum wrinkles on each of the branes, making some regions hotter than others.

Too perfect?

In taking on a sacred cow like inflation, Steinhardt and company were bound to garner a strong reaction. The first came from Stanford University inflation theorist Andrei Linde. Along with his Stanford colleague and wife Renata Kallosh and Lev Kofman of the University of Toronto, Linde published an on-line critique a little more than a week after the first ekpyrotic paper was posted. Linde, among others, doubts that density fluctuations on either brane could survive the creation of a "singularity" — a point of infinite temperature and density where time stops and conventional physics breaks down — caused by the brane collision. "That would be like throwing a chair into a black hole, which would vaporize the particles of the chair, and saying it somehow preserves the shape of the chair," he says.

"What looks like a singularity in four dimensions may not be one in five dimensions," counters Steinhardt. "When the branes crunch together, the fifth dimension disappears temporarily, but the branes themselves don't disappear. So the density and temperature don't go to infinity, and time continues right through. Although general relativity goes berserk, string theory does not. And what once looked like a disaster in our model now seems manageable."

The ekpyrotic scenario has also come under attack because of its stringent set of initial conditions, requiring that the two branes be perfectly homogenous, flat, and parallel. "If you start with perfection, you might be able to explain what you see," Linde says. "But you still have to answer the question: Why must the universe start out perfect?"

Inflation rests on assumptions as well. "It works over a broader range of initial conditions, but not an infinite range," Steinhardt says. What he and his collaborators are proposing is conceptually and philosophically different, he adds. "We're saying there is this whole prehistory to the universe, an immense period of time before the Big Bang that is exponentially longer than the inferred age of our universe, during which these branes could flatten themselves into their most symmetric, lowest energy state." After the collision, there also would be more time for the branes to settle into equilibrium and reach a uniform temperature.

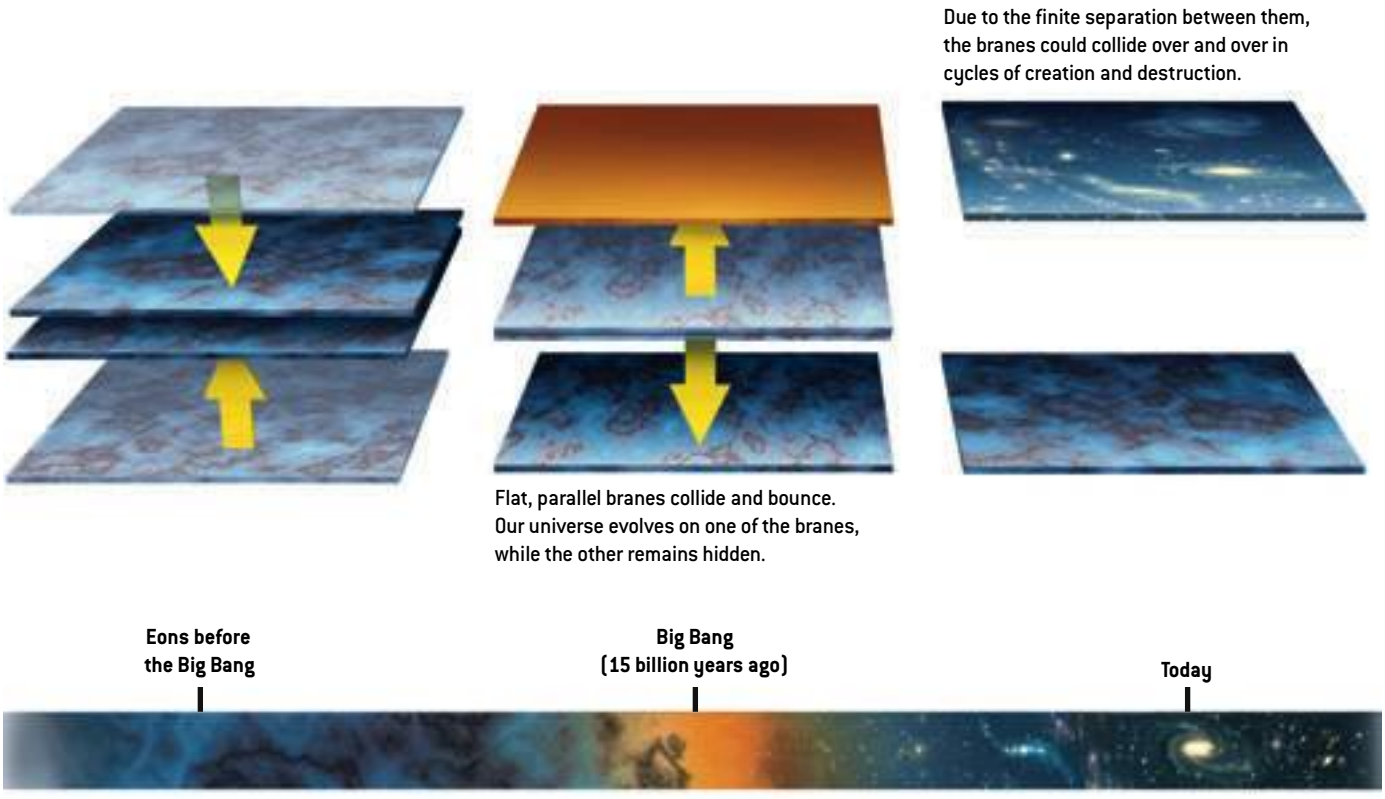
Works in progress

But before astronomers race off to replace inflation with colliding branes, MIT physicist and inflation pioneer Alan Guth has warned that the two scenarios need not be mutually exclusive. In fact, they may complement each other. "In the long run, I think it's inevitable that string theory and M-theory will need to incorporate inflation, since inflation seems to be an obvious solution to the problems it was designed to address — that is, why the universe is so uniform and flat," he says.

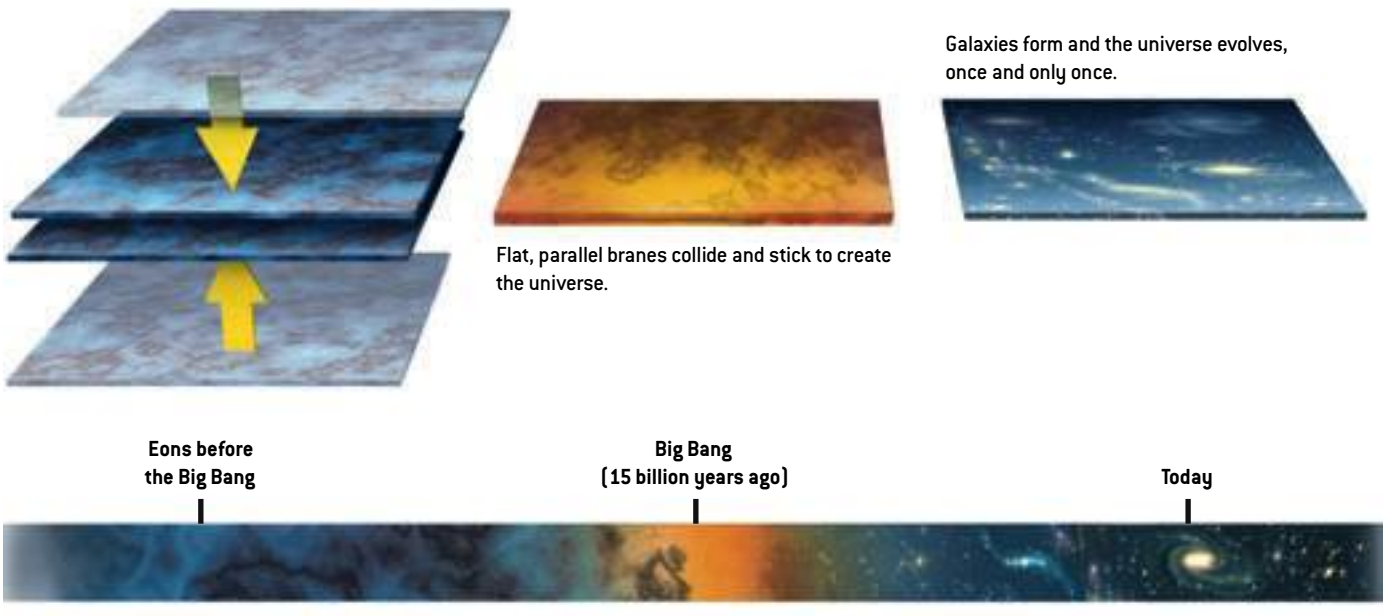
The so-called "branefall" scenario, conceived by New York University physicist Gia Dvali and Cornell physicist Henry Tye,

Steve Nadis, *who edited this issue, is a contributing editor of* Astronomy *and a freelance writer based in Cambridge, Massachusetts.*

Bringing back the bounce: Cyclic model

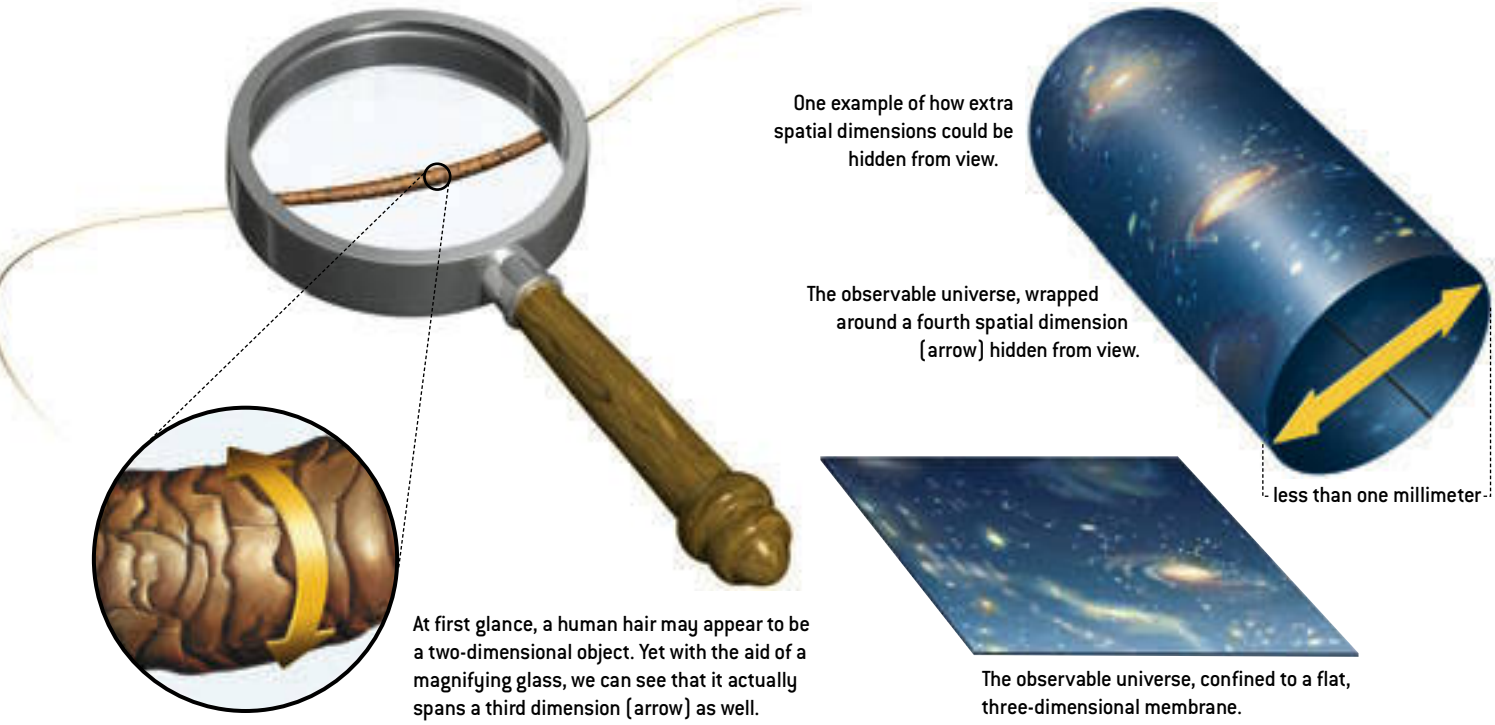

Due to the finite separation between them, the branes could collide over and over in cycles of creation and destruction.
Flat, parallel branes collide and bounce. Our universe evolves on one of the branes, while the other remains hidden.
Eons before the Big Bang
Big Bang (15 billion years ago)
Today

The Big Crash: Ekpyrotic model


Galaxies form and the universe evolves, once and only once.
Flat, parallel branes collide and stick to create the universe.
Eons before the Big Bang
Big Bang (15 billion years ago)
Today

WHICH WAY DID IT GO? M-theory opens new avenues for probing the history of the universe by abandoning the notion that the Big Bang is the origin of space and time. Building on their ekpyrotic model (bottom), Paul Steinhardt and his colleagues recently developed a cyclic model of universal genesis (top). This model states that, rather than sticking after collision, parallel membranes immediately separate. *ASTRONOMY:* ROEN KELLY

Extra dimensions: Where are they?



At first glance, a human hair may appear to be a two-dimensional object. Yet with the aid of a magnifying glass, we can see that it actually spans a third dimension (arrow) as well.

One example of how extra spatial dimensions could be hidden from view.

The observable universe, wrapped around a fourth spatial dimension (arrow) hidden from view.

less than one millimeter

The observable universe, confined to a flat, three-dimensional membrane.

EXTRA DIMENSIONS POSE PUZZLES. Although their influence may be huge, hidden dimensions may be too small for us to detect. And while the usual four dimensions of space-time may be infinite, this need not be so for any extra dimensions. In fact, extra dimensions may occupy spaces millions of times smaller than subatomic particles or perhaps as large as one millimeter. A human hair and a magnifying glass provide an analogy. *ASTRONOMY:* ROEN KELLY

attempts to do just that. Dvali and Tye argue that standard inflation could proceed during the interval when two parallel branes slowly drift toward each other. The attractive tug between branes — fueled by gravity and other string forces — provides a source of potential energy that stays virtually constant, even while space itself expands like mad, which is a feature of standard inflation. One virtue of the Dvali-Tye model is that it presents a geometrical picture that shows where the energy sustaining inflation comes from.

Yet Turner, for one, is not yet convinced that floating branes can solve our outstanding cosmic puzzles. "It doesn't take a genius to say that all of the ideas out there today are wrong — or incomplete, at best. We're still at a very early stage of understanding the extra dimensions (assuming they exist) and their cosmological implications."

No one disputes the proposition that M-theory is a work in progress. And since it's being billed as a possible "theory of everything," it could take a long time to nail down the details. "Even though we don't know the full theory, there's still a lot we can do with confidence," says Tye. "In the same way, we know that Newton's laws are just part of the story, but we use them all the time. They work fine so long as you pick the right regime."

Columbia University's Brian Greene agrees that the new physics is still taking shape, but he considers the interface between cosmology and string theory to be "the most fruitful place to be working today." Greene thinks cosmology offers the best opportunities to test ideas from M-theory and string theory because the energy produced in accelerator experiments is more than a quadrillion times too small. "We've been working on this theory for more than two decades with no new data."

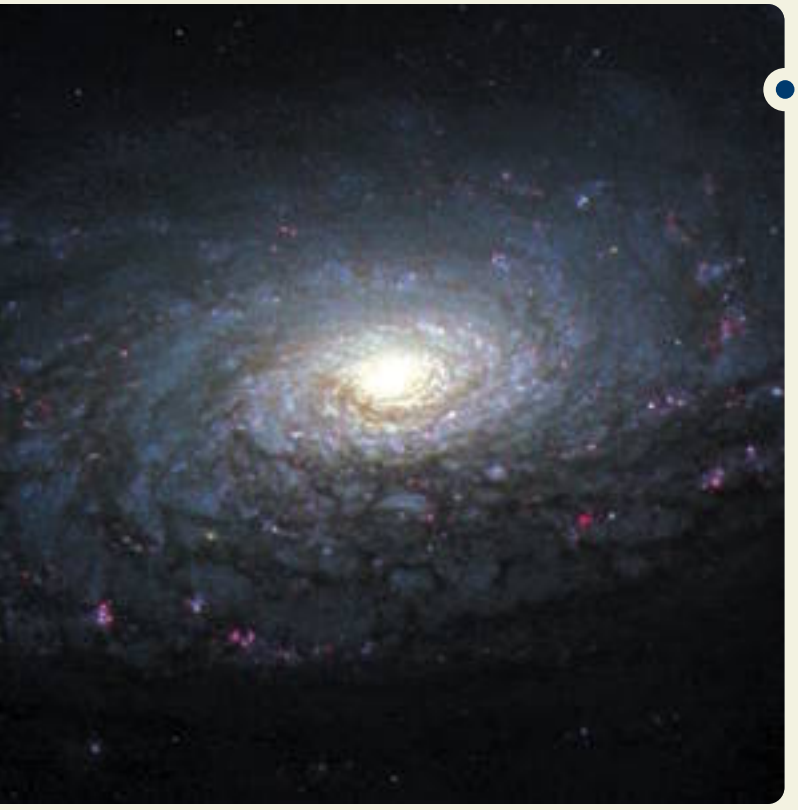
> "The Big Bang theory has been incredibly successful, but it's really only a theory of what happened after the Big Bang." – Michael Turner

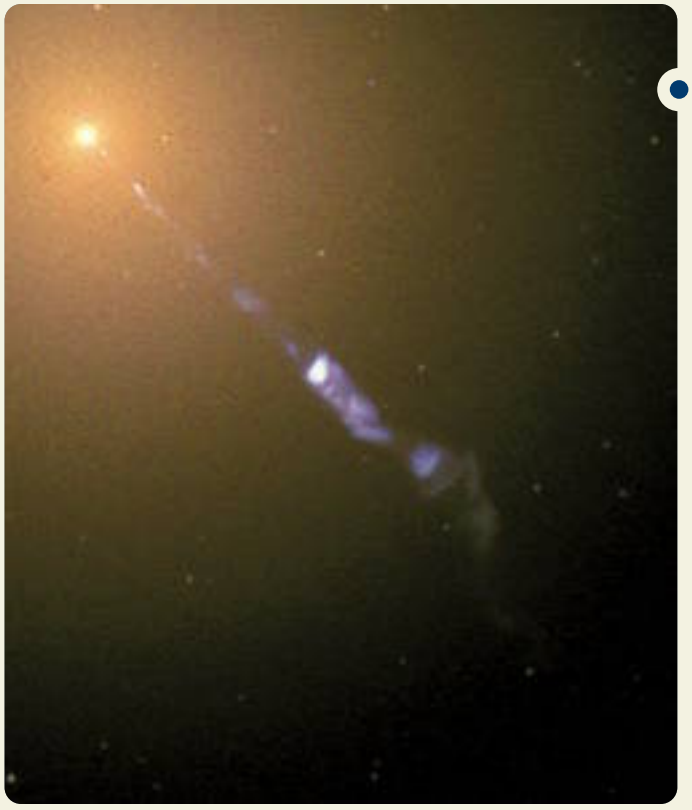
By searching for specific features in the cosmic microwave background (CMB), Greene and his colleagues hope to find "observable signatures that could tell us we're working with the right theory." That signature, in the form of tiny variations in CMB temperature, would be extremely small, assuming it could be found at all. "It would be nice to know I haven't devoted my career to something that is garbage — that we just might have a tool to apply to questions, such as the origin of the universe, that we couldn't get at before," says Greene.

the Coma-Virgo CLUSTER

THE COMA-VIRGO CLUSTER OF galaxies contains more than 2,000 known members and lies about 45 million light-years away. The biggest collection of galaxies in this part of the universe, the Coma-Virgo cluster is vastly larger than the Local Group, home to the Milky Way. Studies of the Coma-Virgo cluster led Edwin Hubble to devise his scheme for classifying galaxies into spirals, ellipticals, and irregulars.

Above, **NGC 4013** /// STScI





Top left, **M63** /// SUBARU TELESCOPE

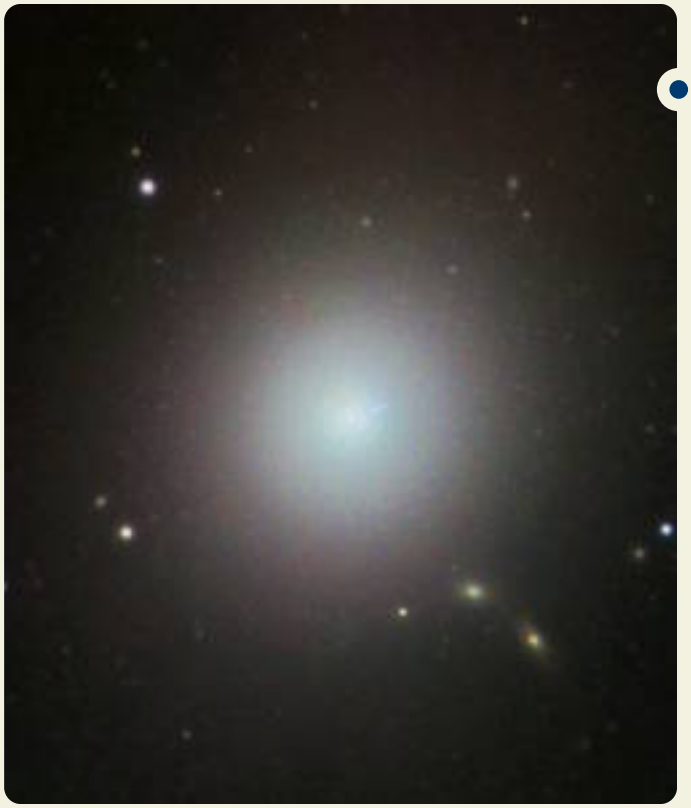
Top right, **M87** /// STScI

Above, **THE SOMBRERO GALAXY (M104)** /// STScI

Top left, **M61** /// ROBERT GENDLER

Top right, **HEART OF THE COMA-VIRGO CLUSTER** /// CFHT

Above, **M63** /// ROBERT GENDLER



Top left, **M94** /// ROBERT GENDLER

Top right, **CORE REGION OF M87** /// ROBERT GENDLER

Above, **M64** /// ROBERT GENDLER

Top, **CENTRAL REGION OF THE COMA-VIRGO CLUSTER** /// ROBERT GENDLER

Above, **NGC 4449** /// ROBERT GENDLER

Uni

The verse takes shape

Armed with fresh observational data, astronomers are working on a blueprint of the cosmos. /// BY KEN GRIMES AND ALISON BOYLE

"Your theory of a donut-shaped universe intrigues me, Homer."
— *Stephen Hawking, as a guest voice on* The Simpsons

As always then, life is a tale told by an idiot, in this case to a genius. And yet the fact that the world's most famous astrophysicist endorses Homer Simpson's vision of the universe as a take-out snack should not, it turns out, surprise us. The donut — or torus — actually stands high on the experts' short list of candidates for the possible shape of the universe, with the dodecahedron, or soccer ball, being another current nominee. Other specialists insist the range of possibilities is much broader. "Serious observational work to determine the shape of the universe has just started only in the last decade," says Boud Roukema, a researcher at the University of Nicolas Copernicus in Torun, Poland. "The race is on to obtain the first significant results."

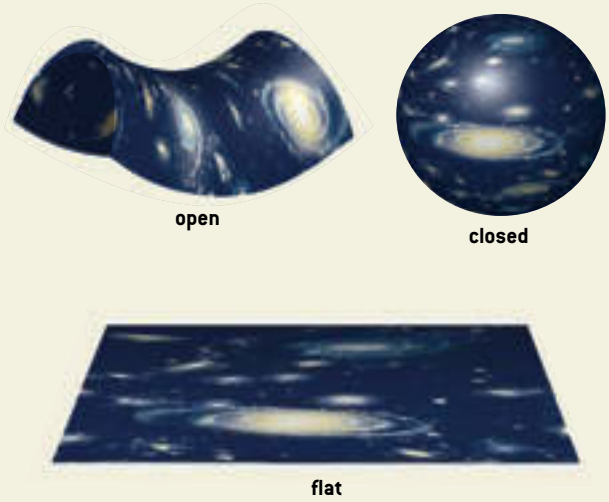
So what are the possible shapes of our universe? Probably the most obvious intuitive answer, based on our normal experience, is that the universe is simply a three-dimensional space, full of energy and matter,

THE WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP) has produced a snapshot of the cosmic microwave background radiation as it appeared when the universe was 379,000 years old. WMAP SCIENCE TEAM

Updated from the October 2002 issue of *Astronomy*

ALL ILLUSTRATIONS: *ASTRONOMY*: ROEN KELLY

/// COSMIC GEOMETRY



The amount of matter in the universe determines its density. The density, in turn, determines the curvature of space-time, which could be flat, spherical (closed), or hyperbolic (open).

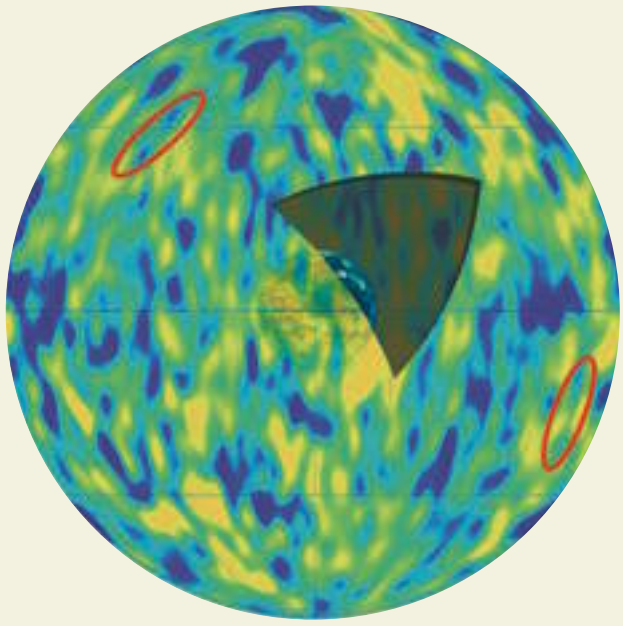
In a closed universe, parallel lines always meet and the sum of the angles in a triangle exceeds 180°.

In a flat universe, parallel lines never meet and the sum of the angles in a triangle equals 180°.

In an open universe, parallel lines tend to converge and the sum of the angles in a triangle is less than 180°.

Current observational data suggest the universe is very near flat, but it may teeter toward open or closed.

/// MICROWAVE MATCHGAME



When astronomers look at the cosmic microwave background (CMB), they are also spying a wall of light known as the "surface of last scattering." This was, in effect, the universe's incipient release of photons, which have traveled the same distance to reach us at the same time (because the speed of light is finite).

Because of this fact, researchers can examine the inside of this "wall" (shown above as the inside of a sphere surrounding Earth) using COBE and WMAP data to look for matching patterns in CMB temperature fluctuations. If matches are found, then cosmologists will be fairly sure of the universe's curvature and could possibly decipher the shape and size of the fundamental polyhedron constituting the universe.

stretching away in all directions like a vast sphere. Some doubt remains about whether this volume is best thought of as finite or infinite. The finite — or "bounded" — version is hampered by a philosophical paradox: What lies beyond the boundary, beyond space's final frontier? And so, almost by default, most of us noncosmologists have come to imagine the universe, if at all, as a kind of infinitely large three-dimensional sphere.

This last feature — three physical dimensions — again seems intuitive from a layperson's viewpoint. The observable universe certainly doesn't have any less than three dimensions, and what could it mean to have more? For mathematicians, however, the answer to this last question is simple: We can represent any point in three-dimensional space with three coordinates, say x, y, and z, where x is the left–right, y the forward–backward, and z the up–down term. By adding a fourth term, say w, we can mathematically represent any point in four dimensions just as easily.

Such a fourth dimension — also known as hyperspace — would exist at right angles to everything. This fact makes it very difficult, some commentators would say impossible, to picture a fourth dimension. Attempts to communicate a sense of this extra "axis" of reality usually are made through analogy. Imagine a world of "flat" beings inhabiting a two-dimensional realm like an infinite tabletop. Such planar creatures and their world would stand in the same relationship to us as we do to a hypothetical fourth dimension.

This hard-to-visualize fourth dimension is particularly intriguing to cosmologists because it can be used to imagine how the universe might be closed. An immediate critique of this idea is that, to the best of our knowledge, the fabric of space certainly doesn't appear to curve toward closure, at least not locally. But, turning to analogy again, imagine you lived on the surface of a sphere. If this sphere were large enough, its curved surface would appear flat — or two-dimensional — in the local vicinity, disguising from its inhabitants the existence of a third dimension that "bends" the other two. Of course, we do live on such a sphere — Earth — whose "extra" third dimension remained hidden to its inhabitants for much of their history. This discovery added a dimension to our conception of the world, and cosmologists are now proposing the same for the universe as a whole.

From donuts to pretzels

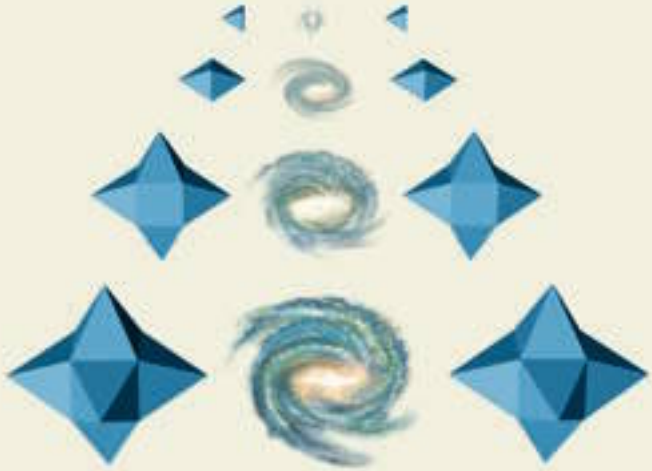
Into what kinds of shapes, then, might the universe be bent in hyperspace? Well, take a square, flat sheet of rubber and bend it until two of its opposite edges join, producing a cylinder. Now join

Ken Grimes *and* **Alison Boyle** *are freelance science writers based in London.*

In a closed, curved universe, light would return to its point of origin. A light source, such as our Milky Way Galaxy, would project a duplicate image of itself. If the universe were sufficiently old, the light would keep circulating the cosmos, making a series of "light laps," and observers would see a series of multiple ghost-like images of the same object.

The hypothesis seems easy to test — find objects that are exactly alike and we can be reasonably sure we live in a closed universe. But there are complications. Because the speed of light is finite, the farther an object lies from the observer, the younger it will appear. Moreover, celestial objects change over time (as represented here by the pyramids evolving into octahedrons) and may look quite different over the course of billions of years. Investigators may be forced to find matches among objects of vastly different ages.

The Milky Way Galaxy is shown here in its progression from a diffuse gas cloud to a protogalaxy and then as the intricate spiral structure we see today.



the two edges of the cylinder, producing a shape known technically as a two-torus, the shape of the common donut. The two-torus has a higher-dimensional analog known as a three-torus. A three-torus theoretically could be made by bending a rubber cube in such a way that all three pairs of matching faces — front and back, left and right, top and bottom — are joined to each other simultaneously. If this "cube" were the entire space of our three-dimensional universe, then the bending operation, which can be explained by recourse to a fourth dimension, would produce the three-torus "donut" favored by Homer Simpson, among other authorities.

Again, this concept is easier to model mathematically than it is to picture. A computer simulation of a three-torus world simply makes opposite cube faces contiguous with each other. The classic Asteroids video game did this in one less dimension: objects leaving the screen at one edge instantly reappeared at the opposite edge. Now imagine a cubic Asteroids screen, where objects passing out through one square face instantly re-enter through the opposite one, and you have fashioned your own simulation of a three-torus world.

Just as donuts come in many flavors, they also can be made in different ways. Janna Levin of the University of Cambridge notes, "If we artificially bend a hexagonal tile into three dimensions and glue the sides together, what we find is another way to make a torus." And why stop with only six faces? An octagon, with its eight triangular faces paired (or "glued"), would produce a figure-eight, or double-holed pretzel— another popular snack item, coincidentally or not.

Beyond the edge

This game of cosmic origami generates universes of a definite shape and of a finite size, and yet without the problematic "edge" of earlier models. Again, it helps to think of our analogy in three dimensions. "The surface of our Earth is a definite shape and a finite size," observes Levin. "And yet it does not have that 'edge' that Renaissance explorers feared to sail over." In fact, any travel in a straight line over Earth's surface eventually results in a circumnavigation of the globe, so that all straight-line journeys end where they began. The same would be true for our closed universe. Like an Asteroids-type starship, any object voyaging outward from Earth in a continually straight trajectory would eventually return to its point of origin, having traversed the entire circumference of the universe.

"Any object" includes, of course, particles of light, or photons. In a closed, curved universe, light itself would describe a curved path, eventually returning to its point of origin. Therefore a light source — such as our own galaxy — would project an image of itself after traversing the circumference of the universe. And the light would not stop there; it would continue traveling. If the universe were old enough, the light would eventually circumnavigate the universe once more, projecting a second image onto its original light-source. And so on for subsequent "light laps" of the universe.

The implications of this idea for contemporary cosmology are truly staggering. When we look up at distant galaxies in the night sky, it is possible that what we are seeing is not a single, vast, or infinite number of galaxies, but the same finite set of galaxies repeated throughout the sky, like torchlights in a hall of mirrors. "The universe could appear vast to us, 'unfolded,' filled with billions of galaxies," observes Jean-Pierre Luminet, director of research at the Paris Observatory. "Yet it would actually be much smaller, 'folded up,' and contain only a small number of objects. A gigantic optical illusion."

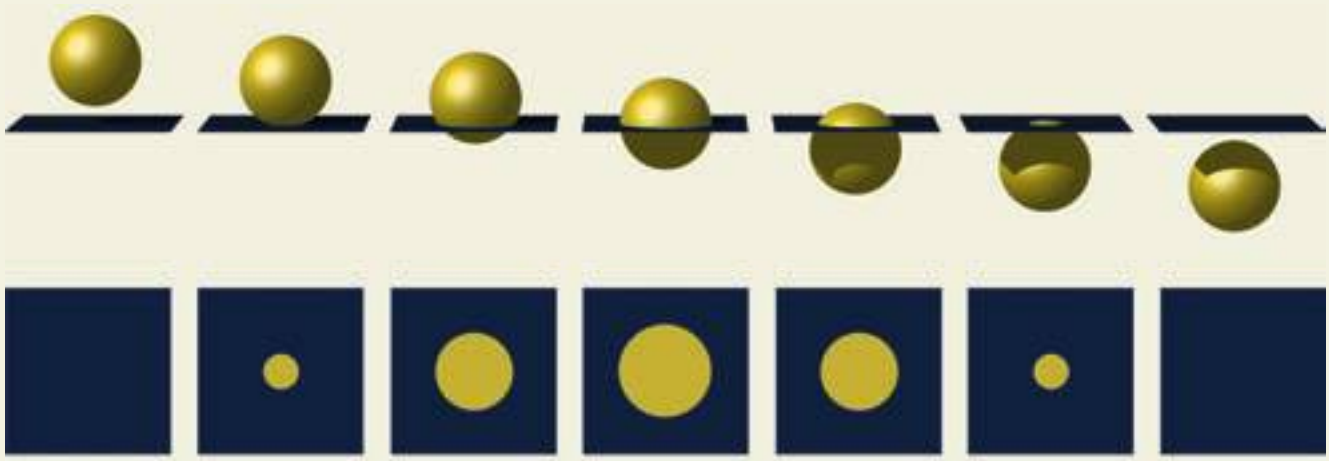
It's all in the fundamentals

Such an illusion would, however, offer the possibility of experimental investigation. If the visible universe is in fact a virtual honeycomb built up from a single building block, or fundamental polyhedron, then study of the sky could allow us to decide what shape that polyhedron is.

And there are many contenders. In normal three-dimensional space, only the cube or regular hexagon of the donut can be fitted together (or "tiled") to produce a honeycomb. However, it turns out that we don't yet know just how "normal" space actually is.

"Space-time tells matter how to move, and matter tells space-time how to curve," goes the pithy summary of Einstein's theory of general relativity. The amount of matter in the universe determines the curvature of space, which could be flat, spherical, or hyperbolic.

A flat universe results from a certain density of matter, known as the critical density. If the density of matter is greater than the



As far as we can perceive, the inhabitants of Earth are creatures of a three-dimensional (3-D) world. However, some cosmologists now theorize that the universe takes on a distinct shape in an imperceptible fourth dimension, also referred to as hyperspace.

A higher dimension is difficult to envision, but one way to get a hint of how it might appear as it interacts with a lower dimension is to consider the illustration above. This depicts what a 3-D realm may look like as it passes through the two-dimensional (2-D) world of flatlanders.

The top row of figures represents how a hypothetical group of 3-D spacelanders would see a meeting and departure of the two realms, while the bottom row shows how the event might look to those shallow souls stuck in the flatlands.

critical density, we get spherical curvature; and for densities less than the critical density, we get hyperbolic curvature. We don't yet know what the density of the universe is because much of its content seems to be in the form of dark matter we can't see. But current observations suggest the universe is exceedingly close to flat, in the same way that any continent on Earth is, on average, close to flat. The geometry of the flat universe is reassuringly similar to what we learned in math classes at school — parallel lines never meet and the angles of a triangle always add up to 180°. But these rules don't apply to the other possible universes. In a spherical universe, parallel lines eventually converge, much as lines of longitude meet at Earth's poles, and triangle angles total more than 180°. In a hyperbolic universe, parallel lines tend to diverge and the angles of a triangle add up to less than 180°.

The number of contenders for shapes that could tile a flat universe is limited, but a spherical or hyperbolic universe offers endless possibilities. Particular shapes of tiles will work only for specific curvatures. Imagine trying to tile your (flat) floor with octagonal tiles — it can't be done because they overlap. However, if you lived in a hyperbolic house, octagons would tile the floor perfectly because the smaller angles they occupy in hyperbolic space mean they can be tiled without overlap. In fact, the octagon-based, double-holed pretzel universe would be possible only in hyperbolic space.

Chasing ghosts in mirror worlds

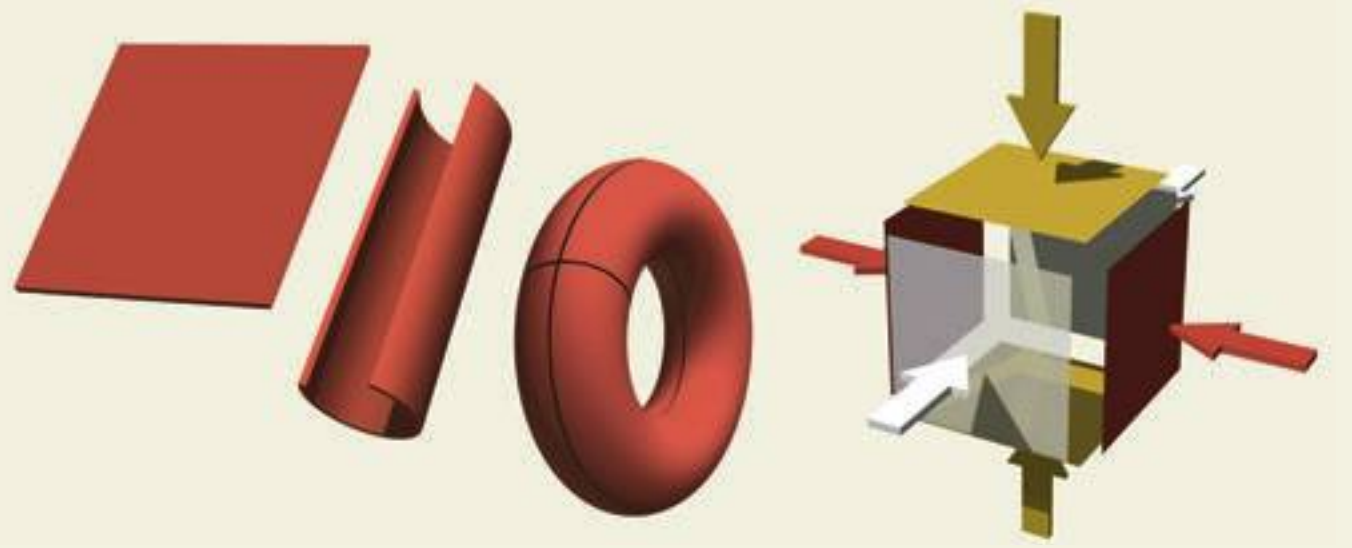
Whatever the eventual shape, there is an obvious method to detect it. As simply put by Roukema: "A single object should be seen in different sky directions and at different distances." In theory, the precise pattern of these object repetitions would allow cosmologists to distinguish between the different proposed shapes of the universe.

The natural original candidates for such research were galaxies themselves. The new theorists have been ransacking current sky maps and astronomical data catalogs in the hope of identifying galaxy twins (or perhaps octuplets, depending on the eventual shape) in different parts of the sky. But this project is turning out to be more problematic than the researchers anticipated. The farther removed in the virtual honeycomb the "ghost cell" containing a galaxy is, the longer its light takes to reach us. This means the same galaxy viewed in different cells would be at different ages in its evolution. According to Levin, "Trying to match galaxies is like trying to match pictures of babies with pictures of their elderly selves." In addition, images from different ghost cells of the universe would reach us from different angles, requiring matching galaxies to be viewed from different directions as well as at different ages.

Another option is to look at quasars. These are the brightest and most distant objects yet discovered, and so they would allow us to look for patterns on larger scales. However, this method suffers from the same problems as galaxy matching. Quasars also look different at different stages in their evolution. And they emit electromagnetic radiation in an asymmetrical way, again making identification from different angles difficult.

Researchers are still hoping that with more comprehensive galactic maps, such as the Sloan Digital Sky Survey, and more sophisticated statistical analysis, galaxies and quasars will help provide a solution. But at the moment, a different method offers the best bet in the race to determine the shape of the universe. This method looks back even farther in time, to the universe's primordial very first light, which we now see as the cosmic microwave background.

When we study the microwave background, we are looking back in time as far as we can go, to a wall of light known as the



The four-dimensional shape of a so-called three-torus is best represented mathematically. However, we can concoct its lower-dimensional analog, the donut-like two-torus, which hints at making a three-torus.

Above, left: The making of a "donut," or two-torus, from a square, flat piece of rubber, appears like a sheet forming a tire.

Above, right: Cosmologists construct a three-torus with a rubber cube that represents the entire 3-D universe. How could it happen? In principle, physicists can envision constructing a three-torus object by bending the cube in such a way that all three pairs of its matched faces are glued together to form a single object.

"surface of last scattering." Immediately after the Big Bang, the universe was a seething mass of particles and photons. Photons scattered off matter, much as they would off water droplets in dense fog, and couldn't go anywhere. It took nearly 400,000 years before the universe had cooled sufficiently for the particles to combine to form hydrogen, through which photons can pass.

Anything before the last photon scattering is considered the "dark ages," forever blocked from our view, but we can detect the first photons to have escaped. We find them at microwave wavelengths, at a temperature of about three degrees Kelvin (–454° Fahrenheit, or –270° Celsius). Because they all must have traveled exactly the same distance to reach us at the same time (because the speed of light is finite), we see the wall of last scattering as the inside surface of a sphere, with Earth at its center.

So, if the universe is tiled, and there are many different copies of Earth, there must be many copies of this sphere. If the shape of the fundamental polyhedron is small enough, these spheres will intersect along circles. The size of these circles would depend on how much the spheres overlapped, and so it would give an indication of the size of the fundamental polyhedron.

Is the writing on the wall?

Neil Cornish of Montana State University, David Spergel and Eichiro Komatsu of Princeton, and Glenn Starkman of Case Western Reserve are examining data from the Wilkinson Microwave Anisotropy Probe (WMAP) to see if they contain hints of "matched circles" — presumed duplicate features in the sky that would suggest a finite, closed universe. So far their analysis, based on months of supercomputer calculations, has not uncovered any such pairs.

This finding is at odds with a theory recently advanced by Luminet, Jeffrey Weeks, and other colleagues, who argued that the WMAP data suggest we live in a closed universe shaped like a soccer ball. They reached this conclusion, in part, because WMAP revealed less-than-expected temperature variations on very large scales. These variations, it is widely held, are produced by acoustic waves in the early universe. The dearth of large-scale fluctuations points to a relatively small, bounded universe because it is impossible to have waves that extend longer than the universe itself.

Cornish rejects this argument, saying, "The defining test of a finite universe is that you could see around it, but there's no evidence to suggest that's the case. Although we can never prove the universe is infinite, we can be sure it's large." Otherwise, light would have had time to wrap around the universe, producing multiple images in the microwave sky. So far, it appears that WMAP's voluminous database bears no trace of such features. "Right now, we can't rule out a kooky shape like a soccer ball," Cornish adds, "but if that's true, we only live in a small patch of it and may never see its full extent."

The shape of things to come

Although astronomers are finally getting clues about the shape of the universe — a matter previously restricted to the realm of speculation — it appears we won't be settling the issue anytime soon. The universe may be finite and bounded, and yet too vast to yield to us the secret of its shape. Alternatively, the universe may possess spherical or hyperbolic curvature, and thus conceal its shape among limitless possibilities. Such thoughts are met with quiet stoicism by the new wave of cosmologists: "The universe is what it is," Roukema acknowledges, "not how I would like it to be."

While Homer Simpson is partial to donuts, more thoughtful observers — less susceptible to the dictates of the stomach — are keeping an open mind. They're well aware of the universe's capacity to surprise us time and again.

Going the distance

Without knowledge of cosmic distances, the secrets of the universe would remain hidden. /// BY MARCIA BARTUSIAK

Consider the vexation in not knowing with certainty whether you are 3 feet tall or 6 feet tall, or that the distance from Chicago to Los Angeles is 1,000 miles or 2,000 miles. Buying a new pair of slacks or planning this summer's road trip would be a guaranteed headache. But believe it or not, astronomers are regularly saddled with such uncertainty when it comes to nailing down some of the most fundamental parameters in cosmology.

In the closing decades of the 20th century, astronomers were stalled. The Hubble constant — a simultaneous measure of the universe's expansion rate and key to its age and ultimate dimensions — persistently varied by a factor of two among different collaborations. To cosmologists, not knowing such a fundamental feature of the universe was terribly frustrating.

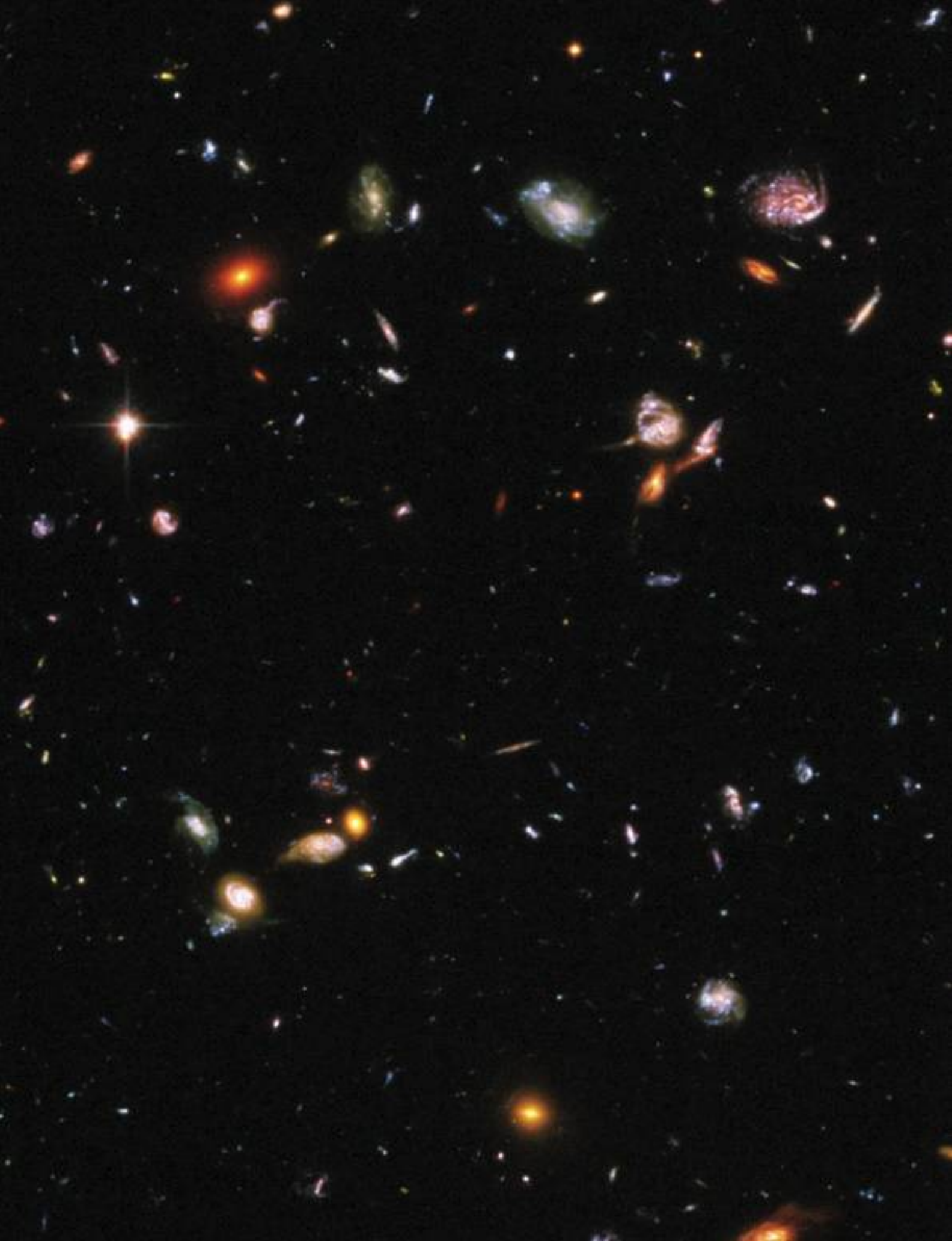
Through no inherent fault or lack of ingenuity among its ranks, astronomy is steeped in a rich tradition of uncertainty when it comes to determining distances to stars, nebulae, and galaxies. Still, despite the difficulty, astronomers have continually devised clever ways to gauge distance, and the good news is that the methods keep getting better and better.

"Twenty years ago there were huge problems," says R. Brent Tully of the University of Hawaii. "We didn't have confidence in our distance measurements even for close-by objects such as the Andromeda Galaxy. But now things are falling into place." New detectors, more powerful computers, and new distance markers — coupled with the use of the Hubble Space Telescope (HST) and powerful ground-based observatories — are at last allowing astronomers to conduct precise surveys. "The revolution came about because we now have the technology to implement ideas that were too difficult in the past," adds Saul Perlmutter of the Lawrence Berkeley National Laboratory in California. In the process, long-held notions about the dynamics of the universe have been completely overturned.

Astronomical distance measurements outside the solar system got a serious boost in 1838, when the German astronomer Wilhelm Bessel used the parallax method to successfully measure the distance to the nearby star 61 Cygni (see

THE HUBBLE ULTRA DEEP FIELD contains galaxies that are estimated to be 13 billion light-years away.

Updated from *Explore the Universe 2002*



2.5 MILLION LIGHT-YEARS AND CLOSING: Cepheids in the arms of the Andromeda Galaxy reveal the proximity of our neighbor. B.J. MOCHEJSKA/FLWO/MDM

"Constructing the distance ladder," page 70).

Measurements beyond the Milky Way Galaxy became possible in the early 1900s thanks to the work of astronomers like Henrietta Swan Leavitt. While working at the Harvard College Observatory, Leavitt discovered a fascinating property of Cepheids — variable stars that regularly pulsate in size and luminosity over periods of just a few days. She noticed that the period of the pulsation correlates closely with the Cepheid's brightness: the longer the period, the brighter the star.

With a calibrated Cepheid period–luminosity relation, astronomers finally possessed the means to figure out a star's intrinsic luminosity, and ultimately its distance. Cepheid variables could be treated as "standard candles" — well understood, reliable brightness indicators.

An object's brightness decreases with the square of its distance. So, by knowing a Cepheid's intrinsic luminosity, which is simply derived from the pulsation period, astronomers are able to determine how far away the star is by seeing how much it appears to have dimmed in their telescopes. Moreover, astronomers have been treated to a significant bonus: As Cepheids are 10,000 times brighter than the Sun, they can be spotted at great distances.

Surveying the expanse (Cepheid variables)

It was observations of Cepheids in the Andromeda Galaxy (M31), the Pinwheel Galaxy (M33) in Triangulum, and NGC 6822 in Sagittarius that allowed American astronomer Edwin Hubble to discover in 1923 a universe beyond our galaxy. He conclusively proved that these "spiral nebulae" don't reside within the borders of the Milky Way Galaxy. But, rather, they are distant galaxies, comprised of billions of stars, lying millions of light-years away.

Hubble also noticed a pattern in his growing catalog of extragalactic distance measurements: The more distant the galaxy, the more its light shifted toward the red end of the spectrum. He concluded that the light waves were getting stretched (redshifted) because the universe is expanding. The farther away the galaxy, the greater its recessional velocity.

Hubble calculated an expansion rate for the universe (now called the Hubble constant) of 500 kilometers per second per megaparsec (one parsec is equivalent to 3.26 light-years, and the prefix "mega" means million), but eventually a better understanding of the different types of Cepheid variables brought the rate down to between 50 and 100 km/s/Mpc.

Shifting that expansion rate into reverse, astronomers can extrapolate back to a time when all matter occupied the same space — the moment of the Big Bang. A Hubble constant ranging from 100 to 50 translates into a universe from 10 to 20 billion years old, respectively. This uncertainty persisted for several decades. What's more, each camp — those defending a low Hubble constant and those fighting for a higher value — fiercely argued that their methods were better calibrated and thus, more precise.

Step by step

Settling the disagreement over the Hubble constant became a high priority in the closing decades of the 20th century. So much so, in fact, that a chief design constraint for the HST was that its aperture be large enough to significantly extend the Cepheid-based distance scale — all the way out to the Virgo Cluster some 50 million light-years away. The 2.4-meter HST mirror allows astronomers to resolve Cepheids ten times farther away than ground-based telescopes can. Since 1993, members of the Hubble Key Project, led by Wendy Freedman of the Carnegie Observatories, as well as other users of HST, have discovered hundreds of new Cepheids in more than two dozen galaxies. As a result, the Key Project now calculates a Hubble constant of 72 km/s/Mpc, give or take 10 percent — just about in the middle of the previously disputed range.

It was important to find Cepheids in galaxies beyond our Local Group and out to the Virgo Cluster. Cepheid distance measurements are the workhorse of the cosmological distance determination business. In fact, astronomers use Cepheid-determined distances to calibrate further distance measurements, forming what's known as the Cosmological Distance Ladder (see "Constructing the distance ladder," page 70). To everyone's delight (and relief), these various markers are agreeing with one another fairly well out to the Virgo Cluster. "It's nice to see that happen," says Freedman. "The distance ladder isn't so shaky anymore."

MULTIPLE DISTANCE INDICATORS lie waiting in galaxies lying at moderate distances such as the Whirlpool Galaxy (M51). JEAN-CHARLES CUILLANDRE/CFHT

Counting headstones (planetary nebulae)

Planetary nebulae — luminous death shrouds of low-mass stars like the Sun — form an additional rung on the distance ladder. As these low-mass stars evolve from their hydrogen-burning phase and move on to the red giant phase, they eventually shed their outer layers of gas into interstellar space, leaving behind an incredibly dense and hot white dwarf core. The sloughed gas subsequently absorbs ultraviolet radiation from the hot stellar remnant and largely re-emits it at a few choice wavelengths, especially a strong green spectral line formed by twice-ionized oxygen atoms. This makes planetary nebulae out to the Virgo Cluster easy to spot with ground-based telescopes.

Planetary nebulae are valuable distance indicators because they are found not only in spiral but also in elliptical galaxies, which don't contain Cepheids. Thus, they can bridge distance scales based solely on one type of galaxy or the other, notes Robin Ciardullo of Pennsylvania State University, who, along with WIYN Observatory director George Jacoby, largely pioneered this technique.

In the late 1980s, Jacoby and Ciardullo used planetary nebulae to measure the distance to the Virgo Cluster. Others, who gauge distances based on the surface brightness of elliptical galaxies, a technique introduced by University of Hawaii astronomer John Tonry, seem to agree. "Despite the fact that our techniques have nothing in common, we get the same answer," notes Ciardullo. Follow-up investigations by the Hubble Cepheid team also match their findings within 10 percent.

Brighter, faster, farther? (Tully-Fisher relation)

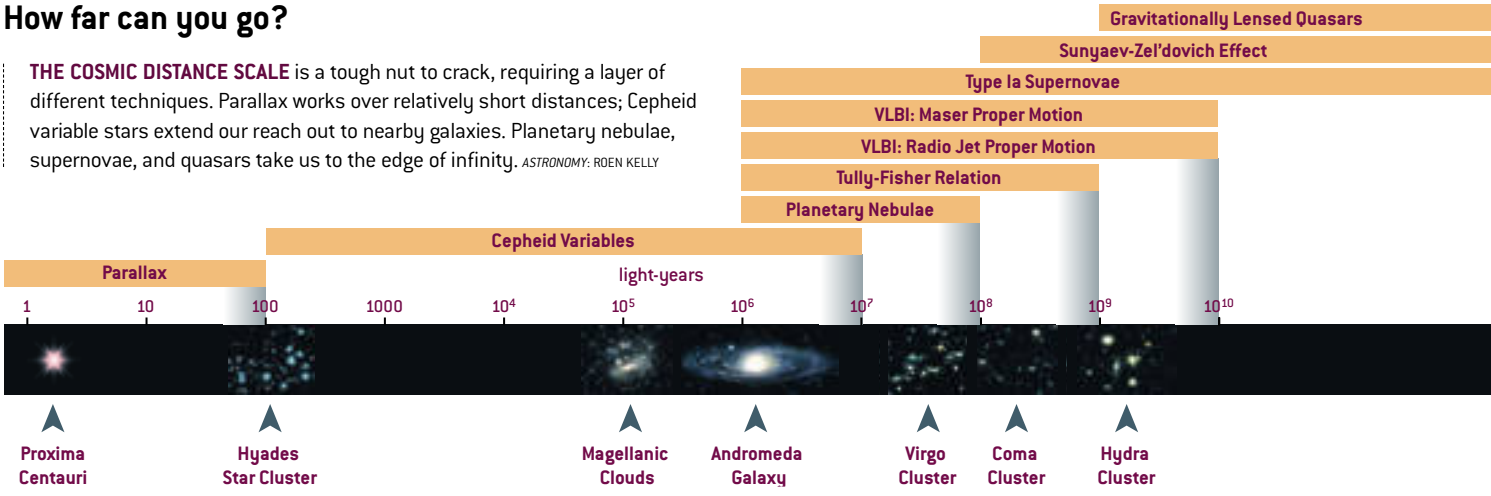
Continuing up the ladder, previous methods are used to calibrate techniques, such as the Tully-Fisher relation, that allow astronomers to measure distances even greater than that of the Virgo Cluster. In the mid-1970s, astronomers R. Brent Tully, now with the University of Hawaii, and J. Richard Fisher of the National Radio Astronomy Observatory, discovered a link between a spiral galaxy's luminosity and its rotation rate.

Bright spiral galaxies, having more mass, rotate faster than dimmer spirals. By determining a galaxy's rotation rate — one way is to measure hydrogen emissions with radio telescopes — astronomers are able to peg its intrinsic luminosity and ultimately use it as a standard candle.

The Tully-Fisher relation is valuable because it's so handy. With other methods, such as using planetary nebulae or Cepheids,

How far can you go?

THE COSMIC DISTANCE SCALE is a tough nut to crack, requiring a layer of different techniques. Parallax works over relatively short distances; Cepheid variable stars extend our reach out to nearby galaxies. Planetary nebulae, supernovae, and quasars take us to the edge of infinity. *ASTRONOMY:* ROEN KELLY



astronomers must hunt for specific objects that may or may not be found. The most recognizable galaxy type in the cosmos — the ubiquitous spiral — can be found anywhere they look. Although this method does have larger margins of uncertainty than other methods, it serves as a useful double-check. Tully and his colleagues have analyzed nearly a thousand galaxies this way, out to about one hundred million light-years.

Super-standard candles (Type Ia supernovae)

In the last five or so years, perhaps the most exciting development in cosmic distance measurements has been the use of Type Ia supernovae as standard candles. "This is a revolutionary old method," quips Perlmutter. Walter Baade first suggested in 1927 that supernovae (what he then called "hauptnovae" or chief novae) would be useful distance markers, but it took many years for astronomers to recognize that there were different kinds of supernovae with differing brightnesses.

Massive stars blow up as brilliant supernovae (known as Type II explosions) when they run out of fuel. Still, there are other ways for stars to become supernovae. White dwarf stars, objects as tiny as Earth yet as massive as the Sun, often reside in binary star systems and are known to steal gas from their stellar companions.

As a white dwarf pilfers mass, it gets compressed under the weight of the added material. If squeezed enough — or to the point that the total mass of the white dwarf reaches about 1.4 times the mass of the Sun — a runaway thermonuclear explosion ensues and the star becomes unstable and explodes in about a second.

Perhaps most exciting to cosmologists, however, is that such explosions (called Type Ia supernovae) yield a similar peak brightness, allowing them to be calibrated as standard candles. And they are so bright — up to ten times brighter than Type II supernovae — that they can be seen from the edge of the visible universe.

Perlmutter started working on this approach a decade ago, in part to prove that supernovae could be reliably spotted and in appreciable numbers. He and his colleagues formed the Supernova Cosmology Project and by the mid-1990s, they were finding batches of supernovae with every observing session, convincing major observatories that it was worth telescope time to examine these objects as distance markers.

Meanwhile, another international group of astronomers, known as the High-Z Supernova Search Team, had long been focusing on understanding the mechanisms of these explosions. "The two teams complemented each other," notes University of California, Berkeley astronomer Alex Filippenko, who has worked with both groups.

The rival teams observed many fields on the celestial sphere once or twice a year, right

MODERN SUPERNOVAE SEARCHES routinely uncover dozens of blasts, like SN1994D (lower left in image), each year. NASA/HST/HIGH-Z SN SEARCH

after a New Moon, when the sky is darkest, using telescopes in Chile and Hawaii. Three weeks later, they would scrutinize the same fields to detect changes. Type Ia supernovae are extremely rare, but by examining hundreds of thousands of galaxies at a time, a dozen or so supernovae usually were sighted in any one session. The teams then followed up with a variety of ground-based telescopes to examine the candidates in more detail.

In 1997, preliminary results indicated that some of these supernovae, a few billion light-years distant, appeared fainter than expected. The teams thought that perhaps supernovae in the past were less luminous because of differing chemical compositions. But because the spectra of the distant supernovae did not differ from stellar explosions nearby, the supernova hunters concluded that it's more likely the universe was expanding more slowly in the past and is now accelerating. This would make the supernovae more distant (and dimmer) than expected.

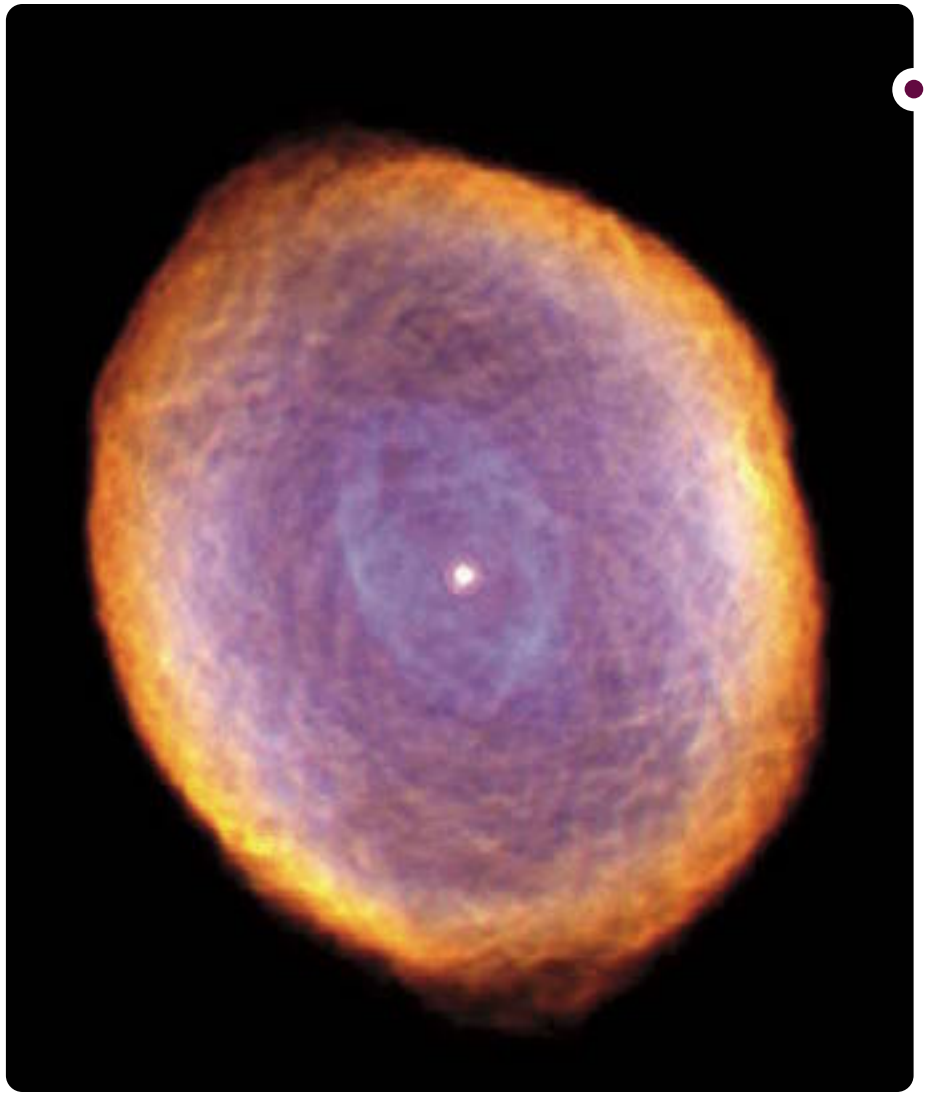
The recent discovery of an extremely distant Type Ia supernova by Adam Reiss of the Space Telescope Science Institute and Peter Nugent at the Lawrence Berkeley National Laboratory corroborates the finding of an accelerating universe. Most astronomers are now convinced that the universe is dominated by a yet-unknown form of dark energy that overpowers the gravitational attraction between matter in the universe to speed up cosmic expansion.

When he first heard the news, Tully had confidence in the accelerated expansion hypothesis, mainly because the finding settled some old disputes. Previously, when distance measurements suggested a high Hubble constant, problems arose. That's because a large Hubble constant implies that the universe is fairly young, generally 10 billion years or less.

But certain stars in the Milky Way Galaxy have been found to be far older than 10 billion years. With an added dark energy to gradually boost expansion over time, the universe suddenly becomes older. "There is no longer a conflict," says Tully. "Everything works much better."

Nevertheless, astronomers like Perlmutter are still proceeding with caution. "What will help," he says, "is going out into space to measure thousands of supernovae each year." And the SNAP (Supernova/Acceleration Probe) satellite is on the drawing board to do just that. The satellite is still in the proposal stage, but the astronomers designing it believe it could be built and launched in four years. With SNAP in orbit, researchers will be able to measure the universe's expansion at various epochs to see how it has changed over time. That will provide clues to what's behind the current acceleration.

Marcia Bartusiak *is a member of* Astronomy's *editorial advisory board. Her latest book is* Einstein's Unfinished Symphony *(Berkeley, 2003).*



PLANETARY NEBULAE, like the Milky Way's NGC 7027, are seen out to the Virgo Cluster. NASA/HST

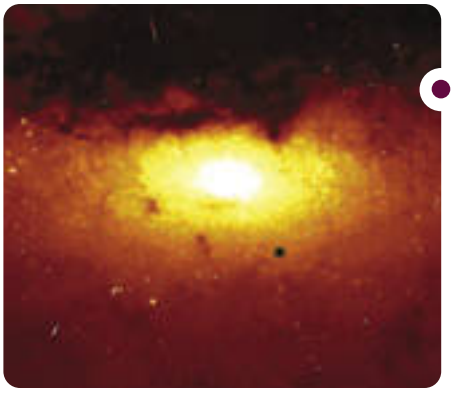
Avoiding the ladder altogether (VLBI)

Over the last decade, astronomers have been developing new techniques that will allow them to skip the distance ladder altogether — one of them is called Very Long Baseline Interferometry.

Using the Very Long Baseline Array (VLBA) — a set of ten radio telescopes situated around the world from Hawaii to the Virgin Islands — astronomer James Moran of the Harvard-Smithsonian Center for Astrophysics and his colleagues recently made a direct distance measurement to spiral galaxy M106.

With the radio telescopes acting as one giant dish thousands of miles wide, they were able to tightly focus on the galaxy's core and measure the velocity of water masers — compact molecular clouds that emit an intense radio signal — swirling in a disk of gas at the galaxy's center. Comparing the masers' intrinsic speed (inferred from Doppler shift of the maser emission) with how fast they appeared to be moving as seen from Earth yielded a distance. (Imagine a boat that is racing across the far horizon at a known speed. Seeing how much more slowly the boat appears to move from shore provides a means of determining its distance with a bit of geometry.) In this way, M106 was found to be nearly 24 million light-years away.

"[M106] was the miracle source," says Moran. "The masers were perfectly placed within the disk." Astronomers using HST to



DEEP IN THE DUSTY CORE of M106, swirling masers act as cosmic beacons. NASA/HST

measure Cepheids in M106 initially came up with a slightly longer distance, about 26 million light-years, but recent corrections to that data bring them closer to the maser-based distance. "We like to look upon the masers as giving the fundamentally correct answer, because it's based on simple geometry," says Moran.

Keeping things proper (quasar jets)

Radio jets shooting out from the cores of active galaxies may reveal their distances in a similar way. Roughly 10 percent of quasars and active galaxies have jets, so there's a good supply of sources for this technique. More importantly, they can be measured to distances far beyond those currently reached by Cepheids or supernovae. Following jet motions with radio telescopes, observers use Doppler shift and magnetic field measurements to compare apparent motion to actual motion.

John Wardle of Brandeis University and Dan Homan, now at Denison University, conducted such a test on quasar 3C 279. The movement of any one feature in the jet is on the order of a few milliarcseconds on the sky. "That's about the height of a fairly tall person on the Moon as seen from Earth," notes Homan. But, as with the masers, radio astronomers can detect such subtle motions with the VLBA. With this grand tape measure, Homan and Wardle arrived at a distance to 3C 279 of about 6 billion light-years. The Hubble constant they calculate from this information is consistent with an accelerating universe deduced from the supernovae findings.

Cosmic spectacles (gravitational lensing)

Another direct-measurement technique that shows great promise is gravitational lensing.

/// CONSTRUCTING THE DISTANCE LADDER: LOCAL DISTANCE MEASUREMENTS

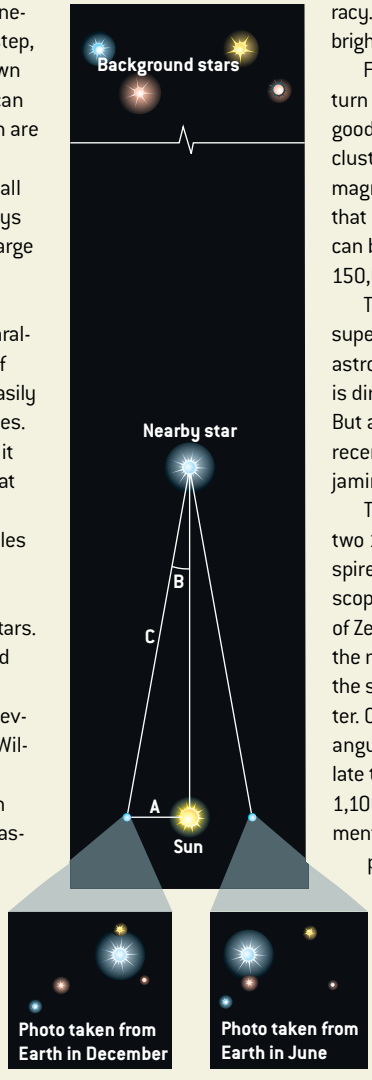
Measuring astronomical distances has never been a one-shot deal. Observers have proceeded slowly, step by step, along a distance ladder. Nearby objects, with well-known properties, are used to calibrate brighter objects that can be used as distance indicators farther out. They in turn are used to calibrate other indicators to even greater distances. One error in that chain affects the accuracy of all the steps that follow. "There's always a weak point," says University of Hawaii astronomer R. Brent Tully. "We charge after the weak point of the moment, settle it, and then something else steps in."

The first (and most reliable) step is trigonometric parallax, which depends solely on geometry and the radius of Earth's orbit, which is very well known. The concept is easily demonstrated by holding a finger 6 inches from your eyes. Looking at your finger first with one eye, then the other, it appears to shift against the background. You'll notice that the shift lessens as your finger moves farther away.

Earth shifts every six months some 186 million miles from one side of its orbit to the other. At each extreme, astronomers get a slightly different line of sight to a nearby star, as seen against the distant background stars. This "parallax shift" allows observers to triangulate and measure the distance to the star (see diagram).

Modern parallax measurements are useful out to several hundred light-years for individual stars. Friedrich Wilhelm Bessel was the first to carry out such a stellar parallax measurement in 1838 from his observatory in Königsberg, Prussia (now Kaliningrad, Russia). He measured the shift for the star 61 Cygni, obtaining a distance of 10.4 light-years (very close to today's accepted value of 11.4 light-years).

Before 1989, only a few dozen stars had parallax measurements with 5 percent error or less. It was then that the European Space Agency's Hipparcos satellite began a four-year mission to measure the shift for more than 7,000 stars to 5 percent accuracy. With lesser accuracy, it pegged the parallaxes and brightness of more than a million stars in the Milky Way.



For stars beyond the reach of parallax, astronomers turn to other techniques. Star clusters, for example, offer a good collection of stars at the same distance. By studying clusters, astronomers can gain a handle on the absolute magnitude of a certain spectral type. They can then use that class of stars as a standard candle farther out. This can be done out to the Magellanic Clouds — about 150,000 light-years.

The premiere standard candles are the Cepheids, supergiant stars that regularly pulsate. For a century, astronomers have known that the period of the pulsation is directly related to the Cepheid's intrinsic luminosity. But a valuable double-check on that relationship was recently carried out by Caltech graduate student Benjamin Lane and his collaborators.

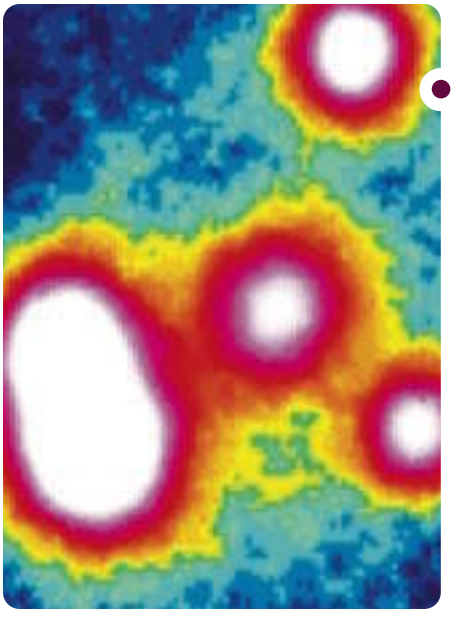
The Palomar Testbed Interferometer is comprised of two 16-inch telescopes, separated by 360 feet, that conspire to generate the resolving power of one giant telescope. The twin instruments were able to resolve the disk of Zeta (ζ) Geminorum, one of the brightest Cepheids in the northern sky. Lane and his team could then observe the star's pulsation and measure the change in its diameter. Comparing this modulation with the corresponding angular change on the sky, the astronomers could calculate the distance directly, which came to approximately 1,100 light-years (give or take 15 percent). With improvements, they hope to better the accuracy to within a few percent. Lane's work serves as a valuable calibration on the luminosity of Cepheids farther out, independent of Leavitt's period-luminosity law.

Other variable stars are useful in a similar way. Yellow RR Lyrae stars, for example, have very short periods (less than a day) and seem to have the same absolute magnitude. Spotting an RR Lyrae thus helps distance determination.

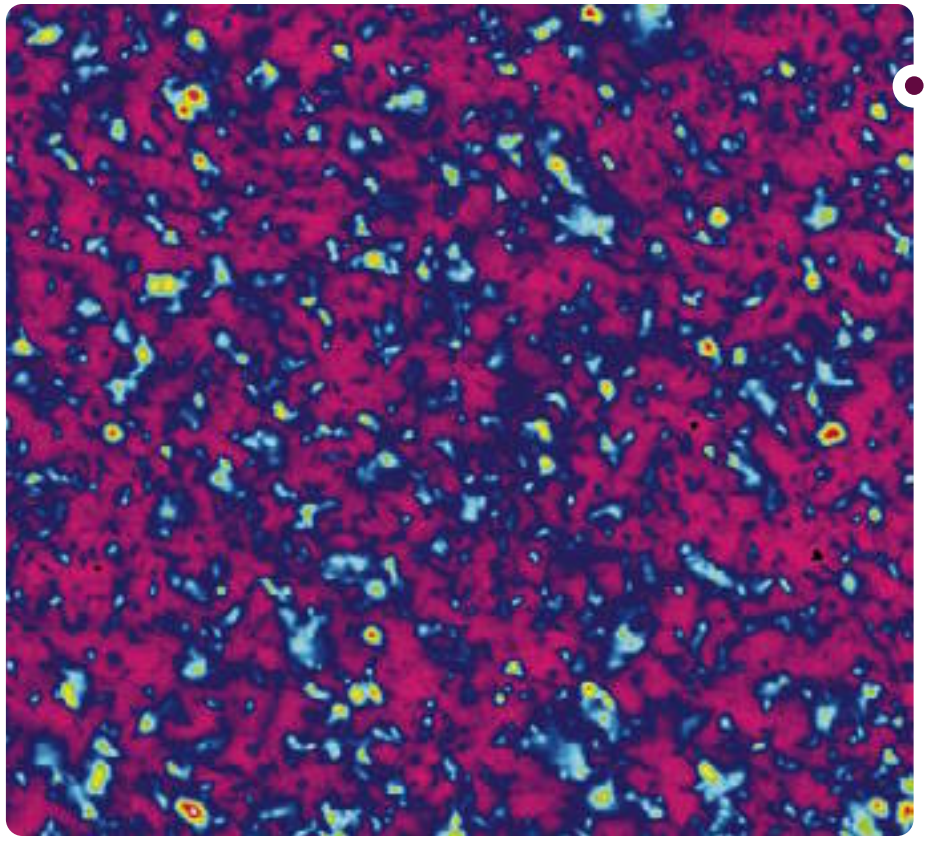
Light from a distant source, such as a brilliant quasar, can be deflected and split by the gravitational field of an intervening object, such as a galaxy or cluster of galaxies. In other words, the galaxy acts as a lens. As a result, observers may see multiple images of the same quasar. With the light beams taking different paths around the galaxy, each traverses a different distance in its journey to Earth. If the distant source briefly flares, each image will reveal it at different times. The first flare will arrive along the beam with the shortest path, and the others will follow along longer paths. By modeling the size and mass of the gravitational lens, astronomers can determine the distances to both directly.

Astronomers have timed such flare delays in several lensed quasars, but it has taken months and even years to monitor the changes in the multiple images. Princeton astrophysicist Edwin Turner and his associates, for example, monitored the flaring of double quasar 0957+561 for more than a year. One image dropped in brightness by about 15 percent; 417 days later, its twin image diminished in the same way. From this, they calculated a Hubble constant of 64.

Recently, astronomers George Chartas of Penn State and Marshall Bautz of MIT used the Chandra X-ray Observatory to document a dramatic fluctuation in a lensed quasar over just a few hours. More sightings like this open up the possibility of using this technique with better efficiency.



A NEARBY GALAXY (center), lying 7 billion light-years in front of PG1115+080, creates multiple images of the quasar. NOAJ/SUBARU



SIMULATED GALAXY CLUSTERS (red clumps) modify existing temperature differences in the microwave background. J. BURWELL/U. PEN/U. SELJAKA

New kid on the block? (Sunyaev-Zel'dovich effect)

Meanwhile, there is renewed interest in a technique based on the Sunyaev-Zel'dovich effect, named after Russian physicists Rashid Sunyaev and Yakov Zel'dovich, who first discussed it some thirty years ago. They pointed out that the cosmic microwave background, remnant radiation released shortly after the Big Bang, can be scattered by intervening matter such as huge clusters of galaxies.

At low radio frequencies, the temperature of the microwave background near the cluster appears lower. At higher frequencies, the background appears brighter because the hot electrons in the cluster scatter the microwave photons and boost their energy. By studying background changes, along with the cluster's X-ray properties, one can assess the thickness of the cluster and deduce its overall size. The cluster's distance then can be determined by comparing its actual size to its apparent size in the sky.

John Carlstrom at the University of Chicago and several colleagues have been studying clusters in this manner with both X-ray space telescopes and millimeter radio arrays in California. So far, they've determined distances to some sixty clusters, out to several billion light-years. Although the Sunyaev-Zel'dovich effect was initially regarded as an independent check rather than as a primary measurement tool, Carlstrom says "its future looks very, very good."

Bringing it home

Astronomers have never claimed immunity from Murphy's Law. As remote distance measurements are agreeing nicely, one of the primary rungs of the distance ladder has been plagued with problems recently. "The biggest uncertainties are in our own backyard," warns Freedman.

For unknown reasons, the distance to the Large Magellanic Cloud stubbornly varies among different indicators. Parallax measurements of Cepheids yield a distance of about 180,000 light-years while other methods, like the use of RR Lyrae stars (see "Constructing the distance ladder," page 70) and eclipsing binaries, suggest shorter distances, from 140,000 to 150,000 light-years.

"No distance measurement technique is completely fail-safe," says Filippenko. But by combining different approaches, we can gain some measure of consistency and, ultimately, a grasp on our universe's dimensions.

What's SIZE got to do with it?

Before setting a limit on the size of large-scale structures, astronomers have to decide what they mean by "structure" and what they mean by "size." /// BY STEVE NADIS

Strange as it may seem, humans are driven to find the biggest of any category — be it mountains, animals, or personal fortunes. Yet when it comes to identifying the largest structures in the universe, the answers have been slow in coming.

Astronomers know that stars assemble by the billions to form galaxies. Galaxies, in turn, clump together by the thousands to form clusters and superclusters. But what, if anything, lies beyond? Will astronomers keep finding ever-bigger entities as they peer deeper and deeper into space? Or is there a fixed size limit beyond which no larger structures will ever be observed? And what are the cosmological implications of either scenario, assuming we can tell the difference?

Like fish unaware of the extent of the oceans surrounding them, astronomers for centuries had no real way of discerning just how large the universe and its constituent parts are. In the past few decades, however, larger telescopes and the development of sophisticated detectors ruled by the precepts of quantum physics have allowed researchers to place some hard limits on the structure of the universe. At the same time, they've developed new techniques for mapping out bigger and bigger chunks of space through galaxy redshift surveys that can be used to find three-dimensional groupings of galaxies millions of light-years across (see "Redshift surveys," page 74). Some astronomers even believe they've found the elusive supercluster size cap — the "end of greatness," as it's sometimes called by cosmologists.

Early indications of such a limit came from the Las Campanas redshift survey, completed in 1994. The survey charted the positions of 25,000 galaxies in three-dimensional space by determining the celestial coordinates of each galaxy and its redshift as an indicator of distance. As the Las Campanas team uncovered superclusters, wall-like assemblages, and vast empty regions of space called "voids," they found that cosmic structures don't become indefinitely big but instead seem to have finite dimensions.

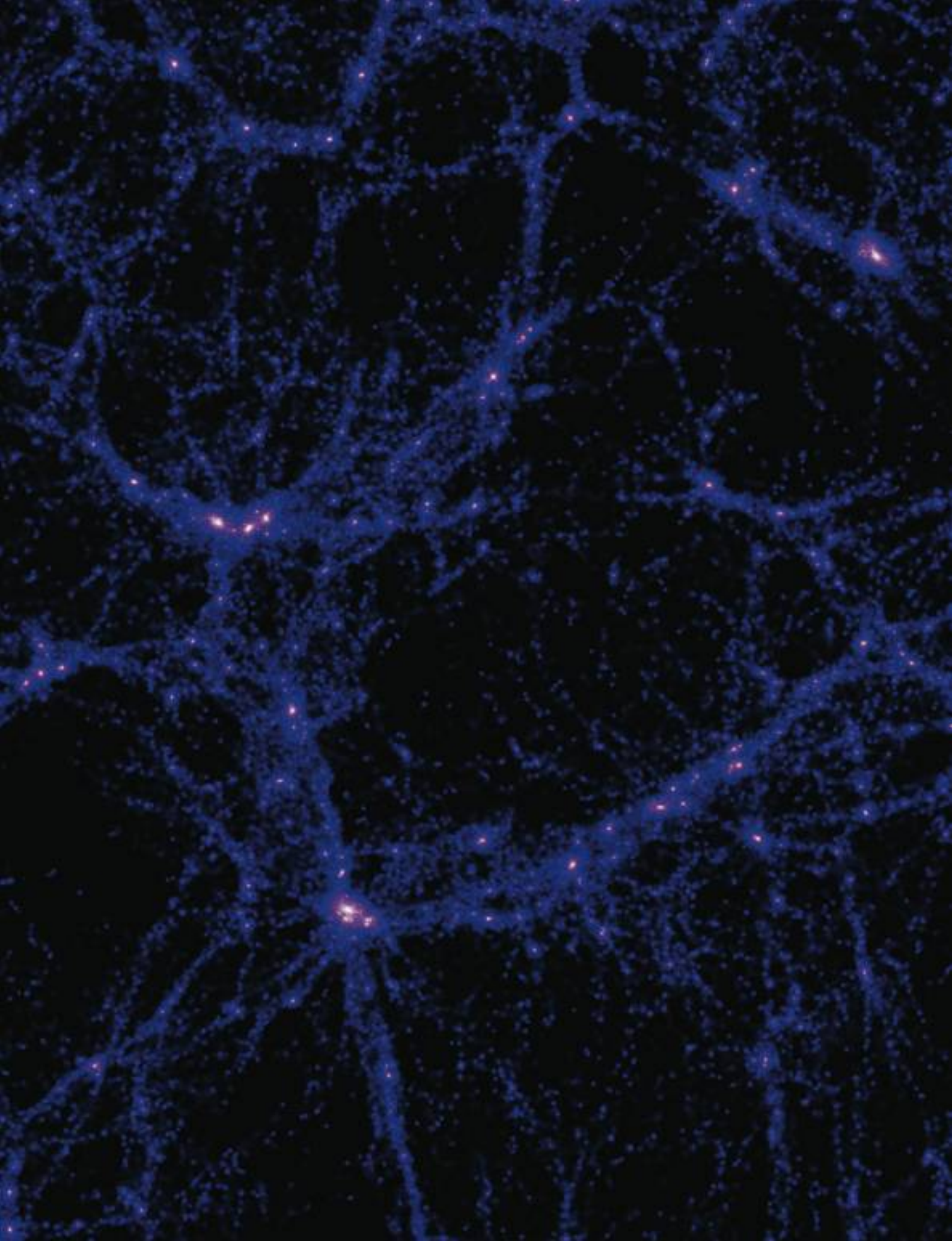
Across the globe, astronomers with the Australian-British redshift survey called 2dF — named for the Two-Degree Field Spectrograph installed on the 3.9-meter Anglo-Australian Telescope near Coonabarabran, Australia — have set the apparent greatness limit at about 300 million light-years. 2dF investigators completed their observations in 2002, obtaining redshifts for more than 220,000 galaxies while creating a map of the local universe out to several billion light-years. "Although we examined just 5 percent of the sky, that's still big enough to constitute a fair sample," says 2dF team member Karl Glazebrook of Johns Hopkins University. "We're confident, because if you take the volume of space we covered [about 13 billion, billion, billion cubic light-years] and divide it into hundreds of smaller chunks, they all look pretty much the same."

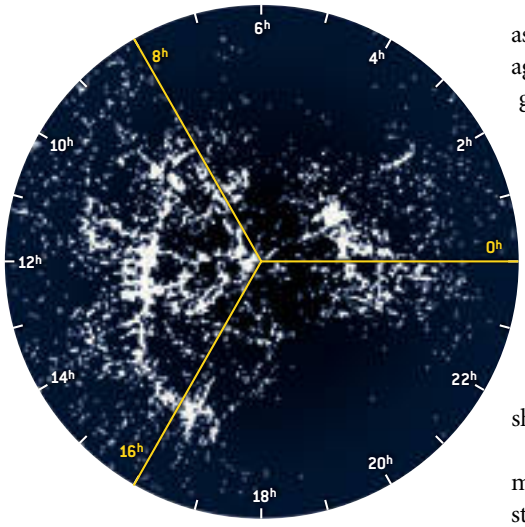
As concepts go, a size cap on superclusters sounds simple enough. Yet it raises a host of unanswered questions, considering there is no general agreement on what astronomers mean by "structures," nor are there any hard-and-fast rules for appraising their size. What's more, several famous exceptions to the 300-million-light-year cutoff exist that further confound matters.

In 1989, for example, two Harvard-Smithsonian Center for Astrophysics (CfA) astronomers, Margaret Geller and John Huchra, announced the discovery of the Great Wall — a vast sheet of galaxies and clusters that spans about 750 million light-years. In 2000, Gerard Williger of NASA's Goddard Space Flight Center and his colleagues discovered another giant clump of galaxies measuring about 600 million light-years across in the constellation Leo. And in 2003, J. Richard

Updated from the March 2002 issue of *Astronomy*

COUNTLESS GALAXIES TRAVERSE VOIDS like a fibrous network of neurons seen in a scanning electron microscope. Instead of the very small, however, these structures are among the largest accretions of matter in the universe. VIRGO CONSORTIUM/J. COLBERG





GIGANTIC GALAXY GROUPS like the Great Wall (600 by 250 by 30 million light-years) continue to puzzle astronomers who study large-scale structures. SAO/M.J. GELLER/H.P. HUCHRA

Gott and Mario Juric of Princeton unveiled the biggest structure yet, 1.37 billion light-years long, based on data from the ongoing Sloan Digital Sky Survey.

These findings will not necessarily topple prevailing theories. "Even with a size limit of 300 million light-years," says University of Maine astronomer David Batuski, "from a statistical point of view you'd expect to find a few things that are significantly bigger. But if we keep finding more and more exceptions to this rule, we might wonder whether the limit ought to be extended."

Much of the confusion stems from the vernacular used to describe giant celestial associations. While astronomers largely agree on the terminology for galaxies and galaxy clusters, their language becomes murkier when discussing substantially larger celestial groupings such as superclusters, which can be arranged like squashed footballs, or sheets and filaments that connect galaxies and clusters. Although certain galaxy-rich regions meet the classic definition of a supercluster — a cluster of galaxy clusters — some filaments, walls, and sheets do not.

"There is no agreed upon set of terms mainly because these things are so hard to study," says University of Hawaii astronomer Patrick Henry. "When you look at a rock, you know what you have. It's much harder to get a grip on these [gargantuan] things."

At the moment, it's not only difficult to define large-scale structures, it's also difficult to gauge their size. "To say how big something is, you first have to say what you mean by size, which is a complicated matter," Glazebrook notes. "Do you mean the radius at which matter is falling in toward a gravitational center, or do you use alternative measures?"

To some degree, the problem stems from limitations of technology: Astronomers can spot bright galaxies and clusters more readily than faint objects, which makes it hard to see the full extent of a giant structure. The North Ecliptic Pole Supercluster, which was discovered in 1985, now appears to be at least twice as big as originally thought, owing to recent observations from the ROSAT X-ray telescope that revealed ten galaxy groups hidden among larger clusters. "X rays allow us to see the finer structure in this supercluster and connections that show how the pieces are linked," explains Christopher Mullis of the European Southern Observatory. "It's like being in an airplane and wanting to know how the population is distributed. If you can only see the biggest cities, you have a fairly crude picture. Once you have the ability to detect small towns, you can get a better sense of how these cities are connected."

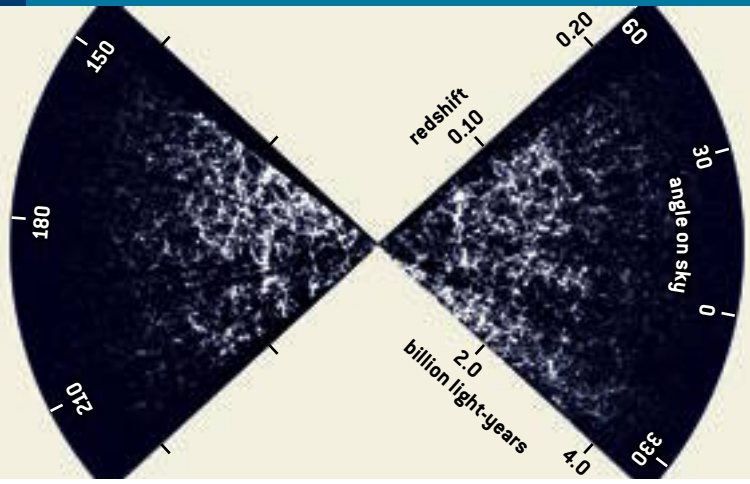
But when astronomers discover clusters and galaxies in the vicinity of a supercluster, how do they know whether these objects are actually part of the grander structure? One simple statistical measure relates to the number of galaxies concentrated in a given volume of space. Areas of high concentration point to what Caltech astronomer Richard Ellis calls "a physically significant structure." Another test uses the distance between galaxies as a way to decide whether a galaxy belongs in a structure.

Nevertheless, even when aided by statistical tools, astronomers still have to make arbitrary judgments about size. They have to decide, for example, how much of a density enhancement above average is needed to call something a structure. "If you use twice the average density as the cutoff, then almost everything in the universe is connected in one huge supercluster," says Batuski. He considers a factor of ten "overdensity" a more reasonable threshold for astronomers to use. "At that level, you get a bunch of individual structures that are relatively isolated from each other. But right now, there isn't a clear physical reason for deciding where to cut it off."

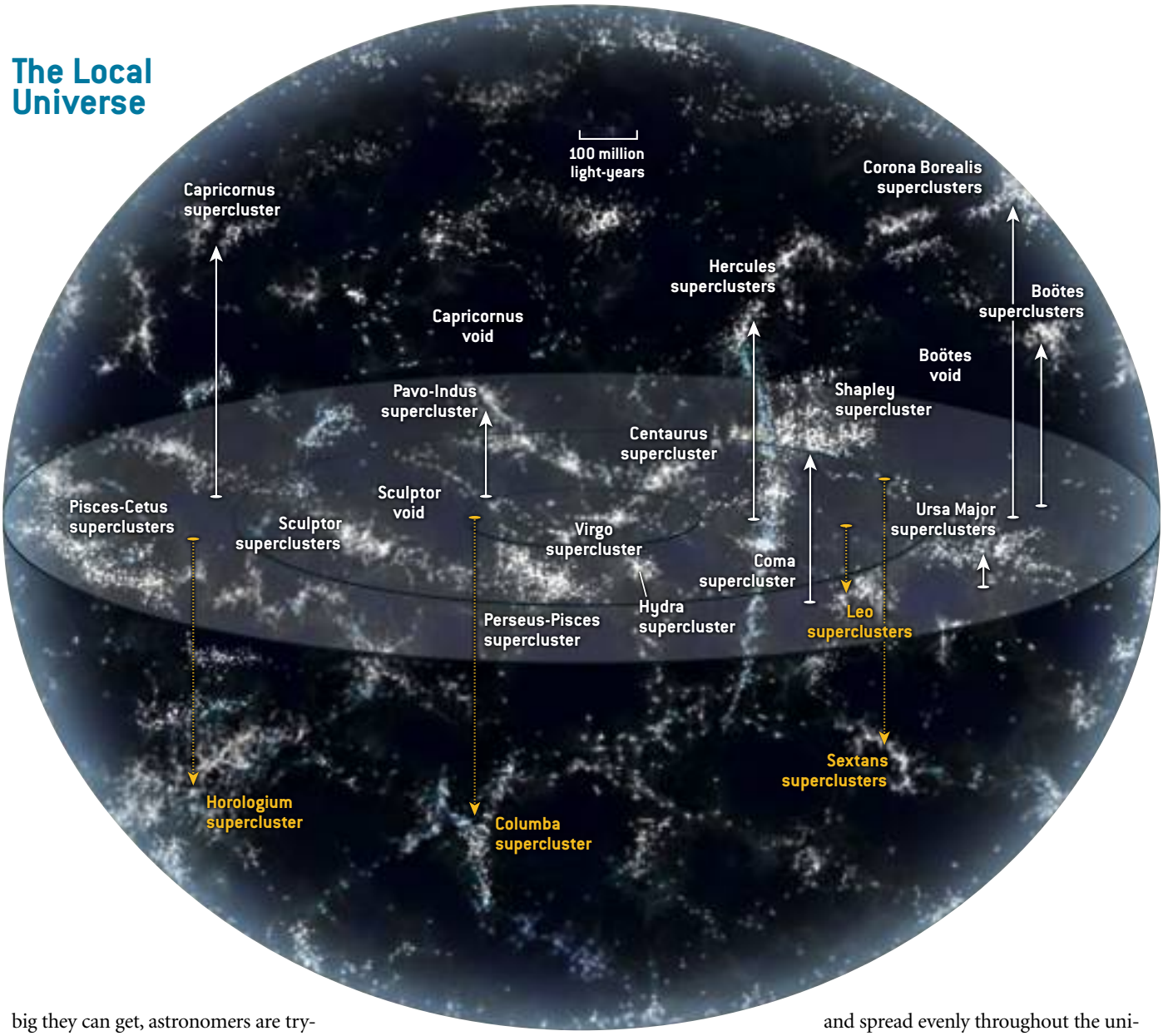
Beyond the debate over what constitutes a structure, how to measure them, and how

Steve Nadis, *who edited this issue, is a contributing editor and freelance writer based in Cambridge, Massachusetts.*

/// REDSHIFT SURVEYS: A LITTLE SLICE OF HEAVEN



Galaxy redshift surveys, like these data from the Australian-British 2dF survey that display the distances and positions of some 220,000 nearby galaxies, are crucial tools for astronomers who trace large-scale structure. Light emitted from objects moving steadily away from Earth gets shifted toward longer (red) wavelengths. Astronomers can measure this effect, called redshift, for galaxies swept up in the expansion of the universe by closely examining their spectral features. Galaxy redshifts (quantified by the ratio of the overall change in wavelength to the expected wavelength if the object were at rest) are directly proportional to distance. Therefore, combined observations of galaxy redshifts and sky positions allow astronomers to map nearby superclusters and voids.



INSPIRED BY EDWIN HUBBLE'S 1923 demonstration that the cosmos is not confined to the Milky Way Galaxy, astronomers have since learned that our galaxy lies deep within the Virgo Supercluster (located at the center of this map). According to astronomers' current picture of the universe, stars clump by the billions to comprise galaxies and galaxy clusters. Galaxy superclusters, the largest structures, can stretch hundreds of millions of light-years across the voids of space. *ASTRONOMY:* ROEN KELLY

big they can get, astronomers are trying to figure out what can be learned from studying huge galactic confederations. "We don't make these maps just because they're pretty," explains Huchra. The goal, instead, is to answer fundamental questions in astronomy, cosmology, and physics.

"Superclusters are so big that their basic pattern couldn't have changed much since the early universe," adds Henry. "So we're seeing what is close to the original pattern of structure, with changes accentuated by gravity." By scrutinizing this pattern, researchers can get clues about the density fluctuations created during the "inflationary" period of the universe, just a fraction of a second after the Big Bang.

Galaxy maps might also reveal whether there is a "preferred scale" for structure in the universe. Astronomers can study this question by means of a mathematical tool called a "power spectrum," which is basically a graph of the observed density of matter in a region versus the average density of space, as a function of scale. They look for deviations from a smooth bell curve in the form of sharp humps or peaks. Based on a preliminary analysis of 2dF data, Ellis says there might be a peak at about 250 million light-years, which would suggest that matter is distributed in lumps roughly that size and and spread evenly throughout the universe. "Soap bubbles in the kitchen sink have a characteristic size," Henry explains. "Whatever made the fluctuations in the early universe might have also made them a characteristic size."

Better data will enable astrophysicists to make more precise calculations of the power spectrum. Indeed, that's a main premise of both the 2dF and Sloan surveys: to compile enough statistics to do what Ohio State University astronomer David Weinberg calls "precision cosmology." These giant surveys, Weinberg says, "are transforming the study of large-scale structure into a precision science." While cosmologists' observations can't match the accuracy of laboratory physicists' yet, he adds, "we can spot something like a 2 percent difference in matter density. And that 2 percent difference might be enough to point us toward new particles or new physics."

Catch a grav w

Two sprawling observatories in Washington and Louisiana will test one of Einstein's great theoretical predictions. /// BY MARCIA BARTUSIAK

The Hanford Nuclear Reservation, currently the nation's prime repository for nuclear waste, sprawls over hundreds of square miles of scrub desert in south-central Washington state. The nearest town, Richland, is 10 miles away. At a key intersection, the road signs direct travelers to either continue west or turn south. There is no sign at all to explain the highway going north, the entrance to the reservation. It is a leftover habit from Hanford's many years as a national secret during World War II.

Five miles down that desolate road stands the Laser Interferometer Gravitational-Wave Observatory operated by the California Institute of Technology and the Massachusetts Institute of Technology. Those in the know simply call it LIGO (pronounced LIE-go). It is a rent-free guest on the Hanford site. Standing alone on the vast plain, a landscape long ago carved flat by the immense outflow of an ancient glacial lake, the complex resembles either a tasteful warehouse or a modern art museum inexplicably placed in the middle of nowhere. An exact duplicate, painted in the same hues of cream, blue, and silver gray, can be found in the pine forests of Livingston Parish in Louisiana, outside Baton Rouge. Together, they form an astronomical tool of the 21st century, a detector like no other before.

Updated from the October 2000 issue of *Astronomy*

MOMENTS BEFORE THEY MERGE, two black holes swirl toward each other in the star-strewn heart of a nebula. The gravity of the black holes distorts the background, while each spins so rapidly the sides are red- and blueshifted. ADOLF SCHALLER

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The signals these two observatories seek are waves of gravitational radiation, or gravity waves as they're called in the popular media. Electromagnetic waves, be they visible light, infrared light, or radio waves, are produced by molecules, atoms, or electrons and generally reveal a celestial object's physical condition — how hot it is, how old it is, or what it is made of. Gravity waves will not convey such information. Instead, they will tell us about the motions of massive celestial objects. "It's an exciting and overwhelming opportunity — a chance to look at a whole new window of the universe," says Gary Sanders, LIGO's deputy director.

Spacequakes

Gravity waves are literally quakes in space-time that emanate from the most violent events the universe has to offer — a once blazing star burning out and going supernova, the dizzying spin of neutron stars, or the cagey dance of two black holes whirling around each other, veering closer and closer until they merge.

Gravity waves will emerge as important scientific objects. They will tell scientists how huge chunks of matter move, twirl, and collide throughout the universe. Eventually, this new method of probing the cosmos may even record the remnant rumble of the first nanosecond of creation — jolts produced by the Big Bang itself.

Marcia Bartusiak, *a member of* Astronomy's *editorial advisory board, adapted this article from her book,* Einstein's Unfinished Symphony *(Berkeley, 2003).*

Inside LIGO's main halls, at both Hanford and Livingston, the ambiance is almost reverential, akin to the response one might feel inside a darkened telescope dome. But this astronomical venture is vastly different. There are no windows to spy on the universe. Instead, two 4-foot-wide tubes at right angles to each other extend out into the countryside for 2.5 miles (4 kilometers). Together, these arms form a giant L in the landscape. The tubes resemble oil pipelines, although they can't be seen directly. Six-inch-thick concrete covers protect them from the wind and rain. In Louisiana, the concrete also has stopped occasional stray bullets during hunting season. A hit could be devastating because the pipes are as empty of air as the vacuum of space. Indeed, they house the largest artificial vacuum in the world.

LIGO was turned on for the first time for two weeks in August 2002, and data have been collected on several brief "science runs" since. So far, there've been no signs of the telltale rumbles predicted by Albert Einstein more than eighty years ago. But LIGO researchers didn't dream of validating Einstein until after fine-tuning their instrument over the next few years.

"The worship of Einstein is the only reason we're here," says Rainer Weiss of MIT, one of LIGO's founding fathers. "If you go to Congress and tell them you're going to try to show that Heisenberg's uncertainty principle is not quite right, you run into blank stares. But if you say you're measuring something that's proving or disproving Einstein's theory, then all sorts of doors open. There's a mystique."

For good reason. Einstein unleashed a revolution that altered the commonplace notions of space and time. His general theory of relativity showed that matter, space, and time are inextricably linked, producing the force known as gravity. Space and time are joined together into an entity known as space-time, whose geometry is determined by the matter around it. According to general relativity, stars and other massive bodies make an impression, quite literally, in the space-time around them, much the way a bowling ball creates a dent in an elastic mat. Planets and comets are attracted to the star because they follow the curved space-time pathway carved out by the stellar orb.

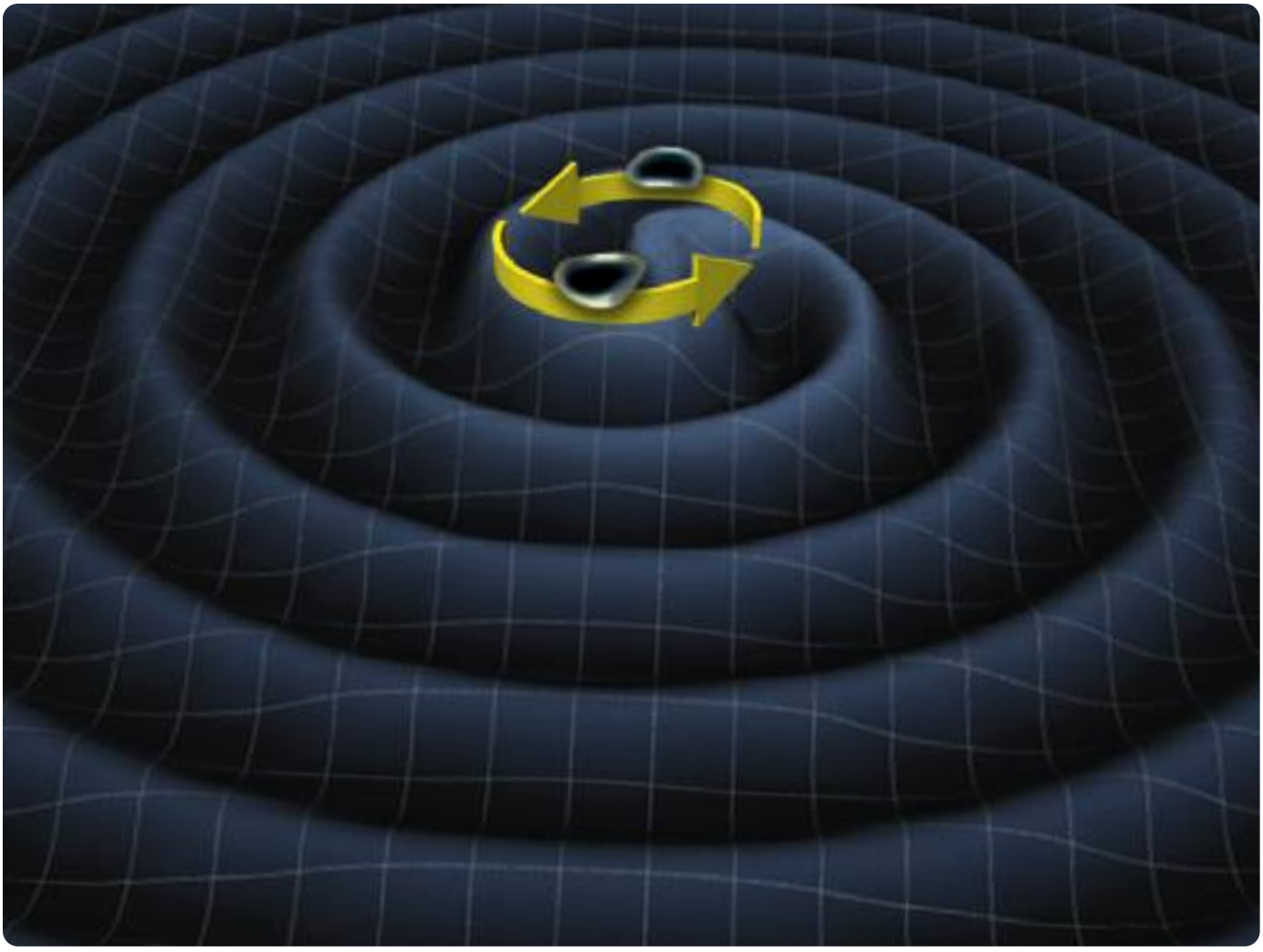
When it was first introduced in 1915, general relativity was hailed as a momentous conceptual achievement but thought to have little practical importance. Times have changed: Global Positioning Satellites, used regularly by hikers, sailors, pilots, and soldiers to keep track of their locations, continually require general relativistic corrections to keep in sync. Moreover, astronomers discovered that intriguing celestial objects such as pulsars, quasars, and black holes could be understood only through the physics of general relativity.

Nevertheless, a major prediction of general relativity still awaits direct observational confirmation: gravity waves. Einstein first mentioned them in 1916, recognizing that just as radio waves are generated when electrons travel up and down an antenna, gravity waves should be produced when masses move about. To understand this phenomenon, imagine

/// LISA

WILLIAM FOLKNER (JPL)/NASA

As scientists work to optimize LIGO, an international team of American and European physicists is planning a space-based gravitational-wave observatory known as LISA (Laser Interferometer Space Antenna). Three identical spacecraft will fly in an equilateral triangle formation far from Earth. Each spacecraft will fire a 3-million-mile (5-million-km)-long laser beam toward one of its partners. This long reach will enable LISA to hear extremely low-frequency gravitational waves emitted by merging supermassive black holes in distant galaxies. Other important sources include the thousands of binary white dwarfs in the Milky Way Galaxy. According to University of Wisconsin-Milwaukee physicist Patrick Brady, these white dwarf pairs are so abundant,"that their gravitational waves will merge to form a background noise at very low frequencies." If approved by the U.S. Congress, the $500-million array could launch as soon as 2011. LISA will then search for, and hopefully measure, gravity waves over the next five years. — *Robert Naeye*



AS TWO BLACK HOLES SPIRAL INWARD toward a fateful merger, they radiate gravity waves. TIM CARNAHAN (GSFC)/WILLIAM FOLKNER (JPL)/NASA

one of the most violent events the universe has to offer — two supermassive black holes crashing into each other in the center of a galaxy. When this happens, space is shaken — and shaken hard. Such a colossal collision would send a spacequake surging through the cosmos at the speed of light. Its waves would not travel through space in the manner light waves propagate. Rather, they would be an agitation of space itself. The waves would alternately compress and extend the fabric of space-time.

Such waves would be deadly near the crash site. They would stretch a 6-foot-tall man to 12 feet and, within a millisecond, squeeze him to 3-feet before stretching him out once again. Any planets in the vicinity would be torn asunder. Fortunately, by the time such waves reached Earth, this cosmic tsunami would be reduced to a subatomic flutter. Were such gravity waves to hit this page, they would be so weak that they would squeeze and stretch the sheet's dimensions by a distance thousands of times smaller than the size of a proton.

Almost no one doubts that gravitational waves exist, for there is already powerful evidence they are real. Two neutron stars in our galaxy are rapidly orbiting each other, drawing closer and closer together. The rate of their orbital decay — about 3 feet per year — is just the change physicists expect if this binary pair is losing orbital energy in the form of gravitational waves. Joseph Taylor and Russell Hulse won the Nobel Prize in 1993 for this discovery. Intercepting an actual wave, though, would offer the ultimate proof, providing astronomers with one of the most radical new tools to explore the heavens in four centuries. This is the motivation behind LIGO, as well as its intended successor, Advanced LIGO — a yet-to-be approved U.S.–German collaboration.

The gong show

This whole endeavor began modestly in the 1960s as one man's quixotic quest. University of Maryland physicist Joseph Weber cleverly surmised that a burst of gravitational energy should set a large cylindrical bar of aluminum vibrating, much like a gong continuing to ring after being struck, although far more weakly. When he reported a detection in 1969, others around the world quickly constructed bar antennae. While most physicists remained highly skeptical of Weber's claims, he initiated a new branch of physics that has never diminished.

The seeds of LIGO, a scheme different from Weber's, can be traced to a classroom exercise three decades ago. To teach the concept of gravity waves during a general relativity course at MIT, Weiss asked his students to envision three mirrors suspended above the ground, their orientation forming the shape of an L. One

mirror would be in the corner, the others at each end. Weiss understood that as a gravity wave travels it does two things: The wave compresses space in one direction — say, north/south — while simultaneously expanding it in the perpendicular direction — east/west. A gravity wave coming straight down on this L-shape set-up would squeeze one of the arms so the mirrors would be closer together, while spreading the mirrors in the other arm farther apart. A millisecond later, as the gravity wave continues onward, this effect would reverse, with the compressed arm expanding and the expanding arm contracting. Weiss was rediscovering an idea that Weber and others had thought of earlier, but Weiss carried out a detailed study that envisioned nearly all the crucial pieces of the observatories now coming on-line.

Weiss figured that a laser beam, bouncing back and forth between the mirrors at each end of the L, could track the expansions and attractions induced by gravity waves. The light would enter the corner of the L, where it is split into two beams, each directed down an arm. After multiple reflections off the mirrors, the beams could be recombined, at which time they interfere with each other (hence the term "interferometry"). Initially, the beams could be set so their waves arrive out of phase. In other words, when added together, the waves from both arms would cancel each other out. When the crest of the light wave in one beam is added to the trough of the light wave in the other beam, the result is darkness, like adding 1 and –1 to get zero. But if a gravity wave causes the arms to expand or contract, the two laser beams would travel slightly different distances. In that case, the recombined beams will be more in phase and would thus produce some light. Traces of a gravity wave could be spotted in that light.

Weiss's concept caught on because it had a distinct advantage. A bar antenna can be tuned to only one gravity-wave frequency (as if it were a radio that could pick up only one station). A laser interferometer, on the other hand, is like a broadband radio. It can detect a wide range of frequencies, making it more versatile for astronomy. Weber's protégé Robert Forward operated the first prototype, a small tabletop instrument, in 1972 at the Hughes Research Laboratories in California. Pioneering groups in Scotland and Germany went on to build interferometers with longer arms, making technological breakthroughs that at last allowed laser interferometry to surpass the bars in sensitivity. A turning point came in 1979, when Caltech lured the Scottish interferometry wizard Ronald Drever to its campus to build an instrument with 40-meter arms, the longest in its day.

From test beds to telescopes

But these were all test beds, not true gravity-wave telescopes. Detecting spacetime tremors requires interferometers with arms miles in length. The subatomic expansions and contractions are easier to measure over long distances. The longer the armspan, the greater the effect. When MIT joined forces with Caltech in 1983, they planned to build two large observatories and waited nearly a decade for funding to arrive. With no guarantee that a gravity wave would be detected, many astronomers and physicists waged a long, hard campaign against LIGO, claiming the money would be better spent on surer scientific quests. But the potential of the science — not to mention strong politicking — eventually overrode those concerns.

With a final construction cost of $292 million (making LIGO the most expensive project ever funded by the National Science Foundation), the Hanford and Livingston observatories are separated by nearly 1,900 miles (3,000 km). The two are more like fraternal than identical twins. The Hanford facility actually houses two interferometers that operate side by side through the arms. There is a full-length detector of 2.5 miles, as well as one half as long. The Livingston observatory has only the full-length interferometer. Each observatory, though, follows the same principles established by Weiss, Drever, and others some three decades ago.

The mirrors, now two in each arm, are made of fused silica. Ten inches wide and four inches thick, each 22-pound (10-kg) cylindrical disk is polished to a smoothness that does not vary by more than 30-billionths of an inch. "If Earth were that smooth," notes LIGO's GariLynn Billingsley, who monitored the mirrors' production, "then the average mountain would not rise more than an inch." Such smoothness is required for light to be reflected over and over again to extreme accuracy. Each mirror is balanced on a single steel wire that is attached to a gallows-like

/// LIGO DETECTION RATES

Major upgrades scheduled to begin around 2006 should increase LIGO's sensitivity tenfold. These upgrades include a more powerful laser, better cushioning to shield against seismic vibrations, silica wiring, and pure sapphire mirrors. The black holes visible to LIGO will be in the range of a few dozen solar masses. The merger of two black holes that LIGO could, at best, barely register at 300 million light-years away should be readily detectable by the improved facility, Advanced LIGO, at 6 billion light-years away. The numbers to the right display large ranges because they heavily depend on theoretical assumptions that can't be verified until the first detections are made.

LIGO

Supernova (within our galaxy)
1 to 3 per century

Black hole/black hole merger
(out to 300 million light-years)
1 per year to 1 per 1,000 years

Neutron star/neutron star merger
(out to 60 million light-years)
1 per 10 years to 1 per 10,000 years

Neutron star/black hole merger
(out to 130 million light-years)
1 per 10 years to 1 per 10,000 years

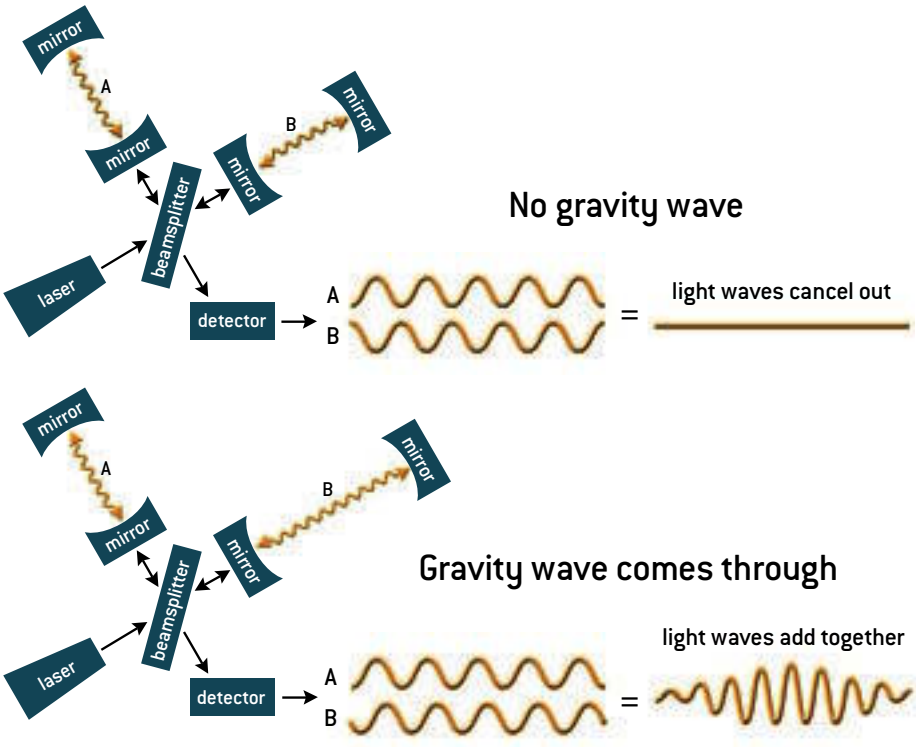
ADVANCED LIGO

Supernova (out to 60 million light-years)
2 to 3 per year

Black hole/black hole merger
(out to 6 billion light-years)
10 per day to 10 per year

Neutron star/neutron star merger
(out to 1.5 billion light-years)
1 per day to 1 per year

Neutron star/black hole merger
(out to 3 billion light-years)
10 per day to 1 per year



IF NO GRAVITY WAVE PASSES through one of the LIGO facilities, the two 2.5-mile arms have exactly the same length. Light beams reflecting within each arm will arrive at the detector out of phase, so they cancel each other out. However, if a gravity wave passes through, one arm will be lengthened and the other compressed by about the width of a proton. The changes in arm length cause the light to arrive at the detector partially in phase, so the beams add to create a signal. *ASTRONOMY:* ROEN KELLY

frame. This support, in turn, rests on an isolation platform, not unlike a car's suspension system, to reduce seismic jitters a millionfold.

Two observatories are needed to rule out local disturbances that might mimic a gravity wave at any one site, such as a passing garbage truck or seismic tremors. A gravity wave will pass through both observatories within 10 milliseconds of each other. In addition, the shape and size of the wave should be identical in both places.

LIGO will be most receptive to frequencies from 100 to 3,000 hertz, which is coincidentally the same frequencies our ears pick up as sound. You could actually listen to the signal, once it is electronically recorded. "It sounds like a hiss," notes LIGO's Albert Lazzarini.

But computers, not ears, sift through LIGO's data. The technique is similar to the way in which military sonar experts search for the distinctive sound of a submarine amid the many noises of the sea. Essentially, as data streams in, it is compared to a "template" — a theoretical prediction of what a gravity-wave signal might look like. Take, for example, the case of two neutron stars spiraling into each other. According to computer simulations, this system can produce many possible wave patterns because the signal depends on both the masses of the neutron stars and their orientation as viewed from Earth. To do a proper search, LIGO will have to continually compare its incoming data against some 20,000 to 30,000 possible signal patterns worked out by theorists.

Neutron star collisions may be the bread and butter of LIGO's trade. Once the detectors are sensitive enough to see hundreds of millions of light-years beyond Earth, they may detect a few mergers per year. LIGO will register the binary's final minutes — a whine that rises rapidly in pitch as two city-size balls of dense matter spiral into each other.

The biggest prize of all will be two black holes colliding. As the twirling holes are about to meet, spiraling inward faster and faster at speeds close to that of light, computer models predict that the whine will turn into a chirp, a birdlike trill that races up the scales in a matter of seconds. A cymbal-like crash, a mere millisecond in length, heralds the final collision and merger; the two black holes become one. This sound would be followed by the diminishing tone of a struck gong, as the newly formed black hole gradually settles down. If LIGO is lucky enough to detect such a signal, it would be the first direct evidence that black holes exist.

Other potential signals include the explosive burst of an asymmetric supernova, a murmur from the Big Bang itself, and the steady beat from a rotating neutron star. "But what if the strongest gravitational-wave signal," asks Lazzarini, "is a belch or burp that arrives sporadically? Then what? You have to assure yourself it wasn't just an amplifier problem or a bad wire." Those sorts of signals — fleeting, unexpected, irregular — will be the most vexing of all, "but they're also where the biggest surprises and most profound discoveries may lie," adds Lazzarini.

LIGO has operated intermittently since 2002, as astronomers prepare for a full year of data collection in 2005 and 2006 at the facility's design sensitivity. LIGO researchers have conceded all along that their first detectors may not register a thing. For its critics, that made LIGO technologically unjustifiable and premature. LIGO was built, nevertheless, on the belief that scientists and engineers couldn't have found solutions without first building a full-size facility to carry out the needed tests.

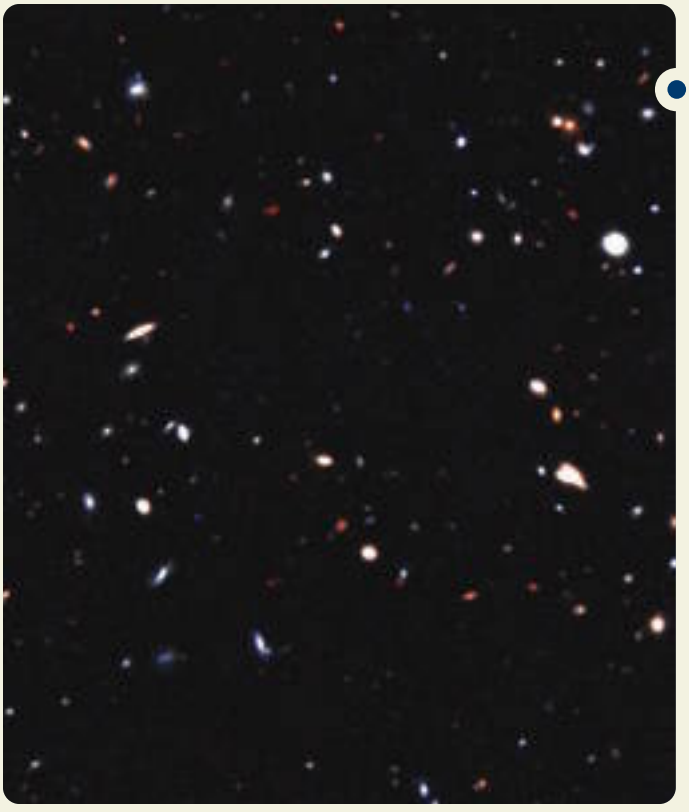
If funding can be secured, U.S. astronomers will team up with German colleagues at the Albert Einstein Institute in Potsdam, Germany, to create Advanced LIGO, which will use LIGO's basic infrastructure while upgrading its scientific equipment. The new, improved observatory should come into full operation around 2010. With a tenfold gain in sensitivity, Advanced LIGO could detect sources hundreds of millions or even billions of light-years away, possibly registering one event a day.

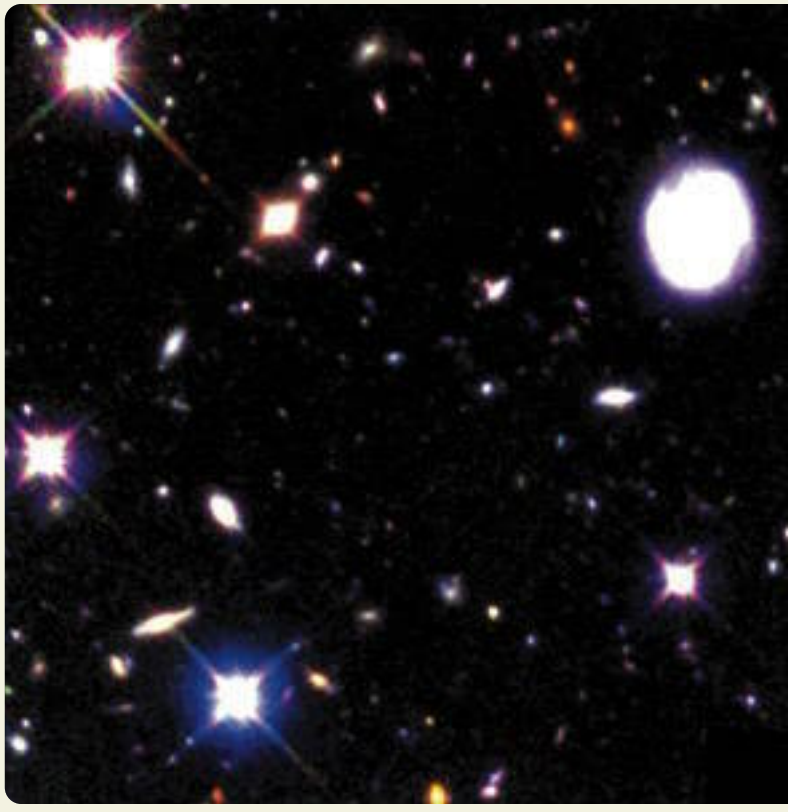
On the other hand, it's conceivable that nothing will be observed. What keeps LIGO researchers at work when no signal is guaranteed? "People take pleasure in solving the technical challenges," answers physicist Peter Saulson of Syracuse University, "much the way medieval cathedral builders continued working, knowing they might not see the finished church." But if there's "a fighting chance of seeing a gravity wave during my career," he adds, "it's definitely worth a shot."

the deep UNIVERSE

AS ASTRONOMERS LOOK TOWARD the most distant galaxies — taking "deep field" (long- exposure) images — they look back in time, viewing the universe as it was in earlier epochs. At the farthest reaches of the visible universe, telescopes on the ground and in space detect galaxies that formed only a few hundred million years after the Big Bang. By comparing early galaxies with those around us, cosmologists hope to discover how our universe became what we see today — and discern how it will evolve in ages hence.

Above, **DISTANT GALAXY CLUSTER** Abell 851 in Ursa Major, infrared light, 1999 /// SUBARU TELESCOPE

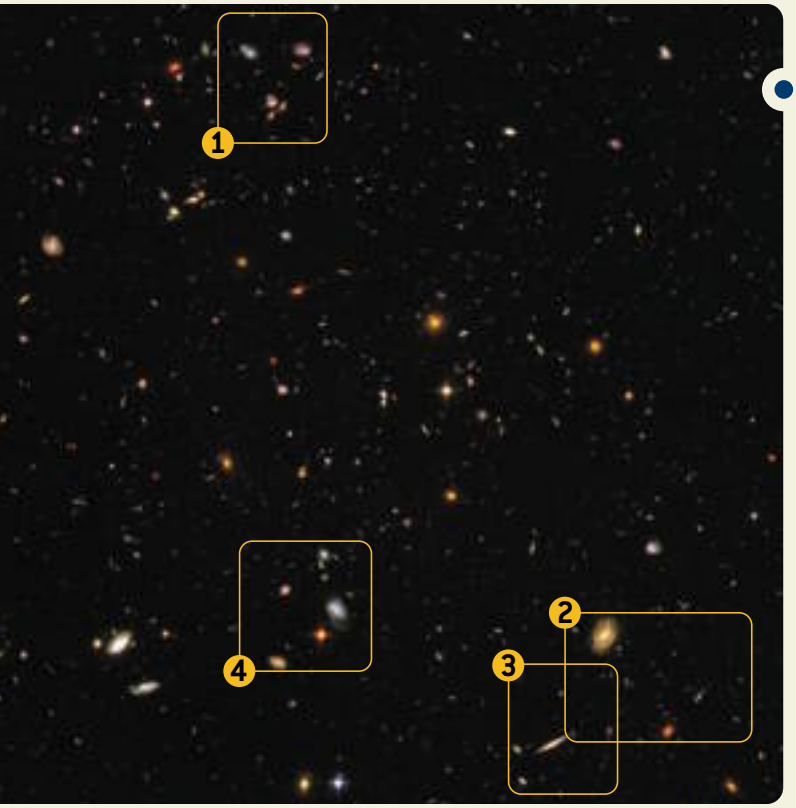


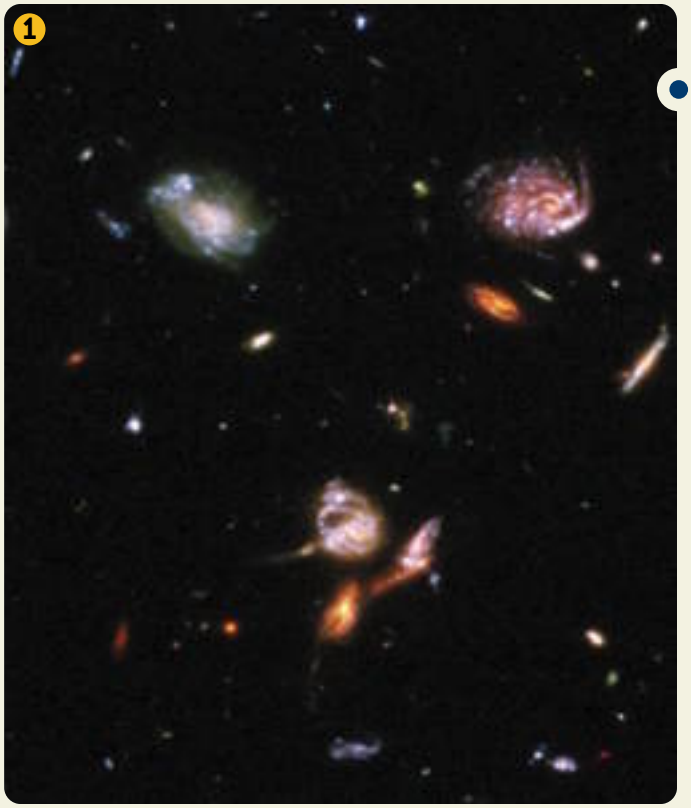


Top left, **SUBARU DEEP FIELD** in Coma Berenices, infrared light, 1999 /// SUBARU TELESCOPE

Top right, **HUBBLE DEEP FIELD SOUTH** in Tucana, visible and infrared light, 1998 /// STScI

Above, **HUBBLE DEEP FIELD NORTH** in Ursa Major, visible and infrared light, 1995 /// STScI

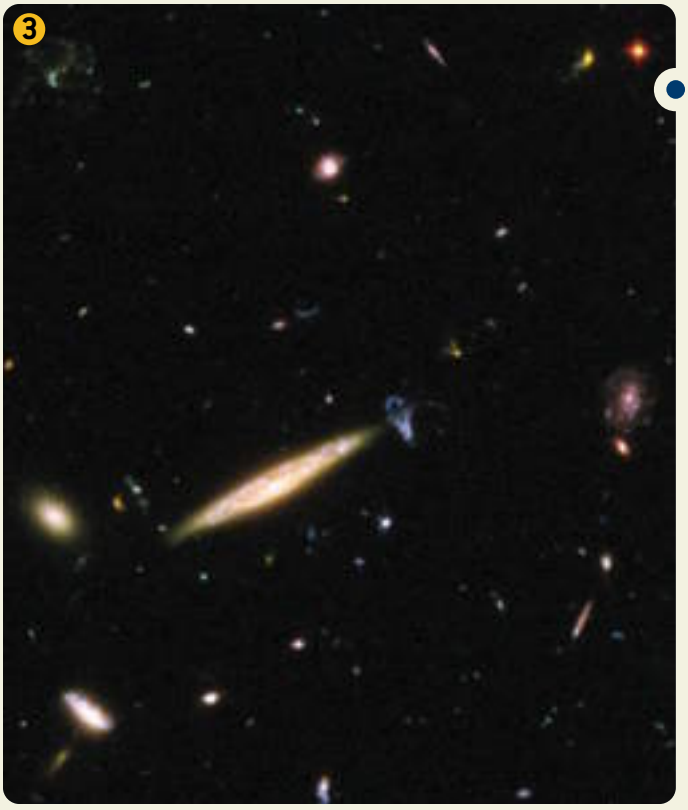


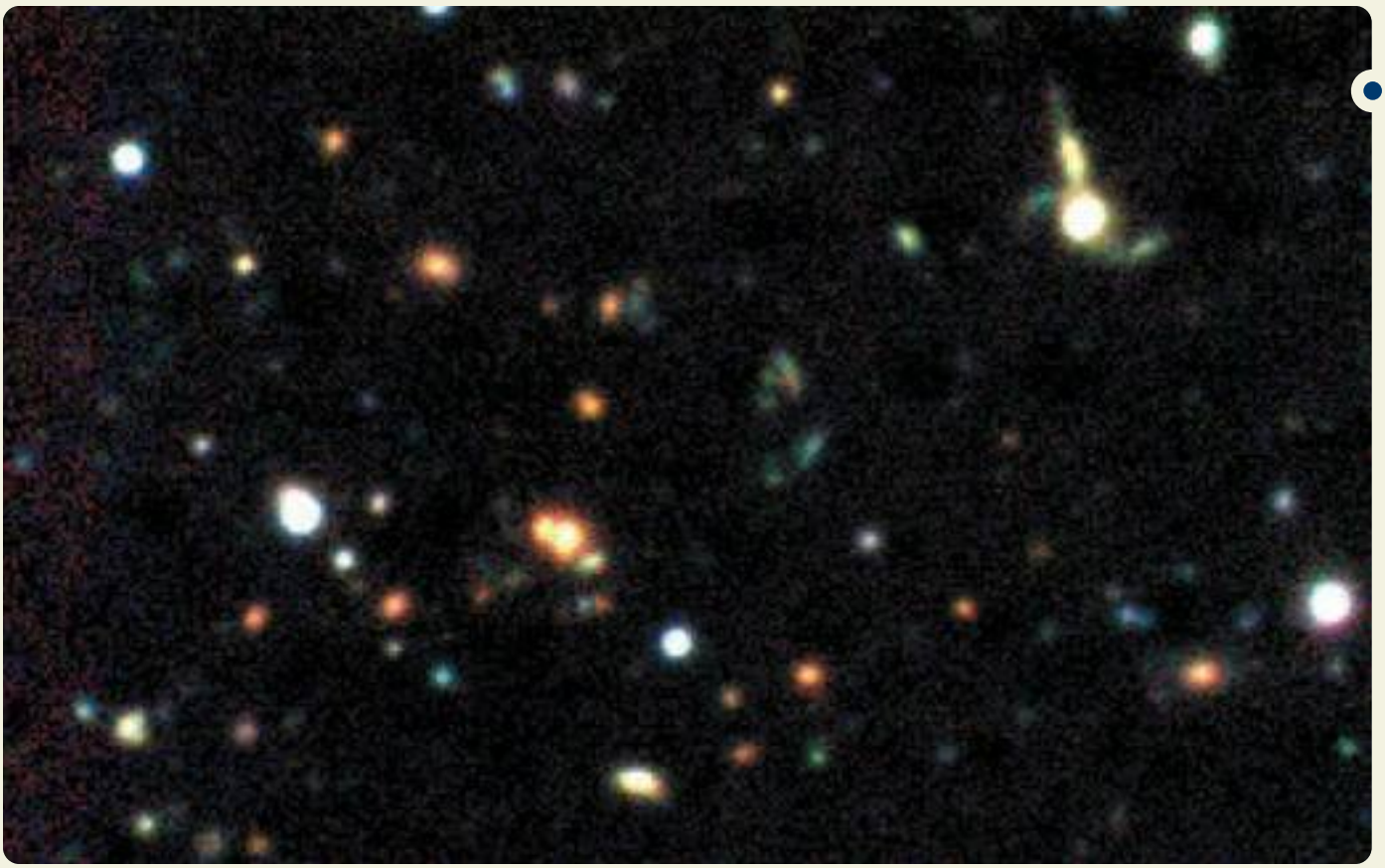


Top left, **HUBBLE ULTRA DEEP FIELD** in Fornax, visible and infrared light, 2003–2004 /// STScI

Top right, **HUBBLE ULTRA DEEP FIELD,** visible and infrared light, 2003–2004 /// STScI

Above, **HUBBLE ULTRA DEEP FIELD,** visible and infrared light, 2003–2004 /// STScI

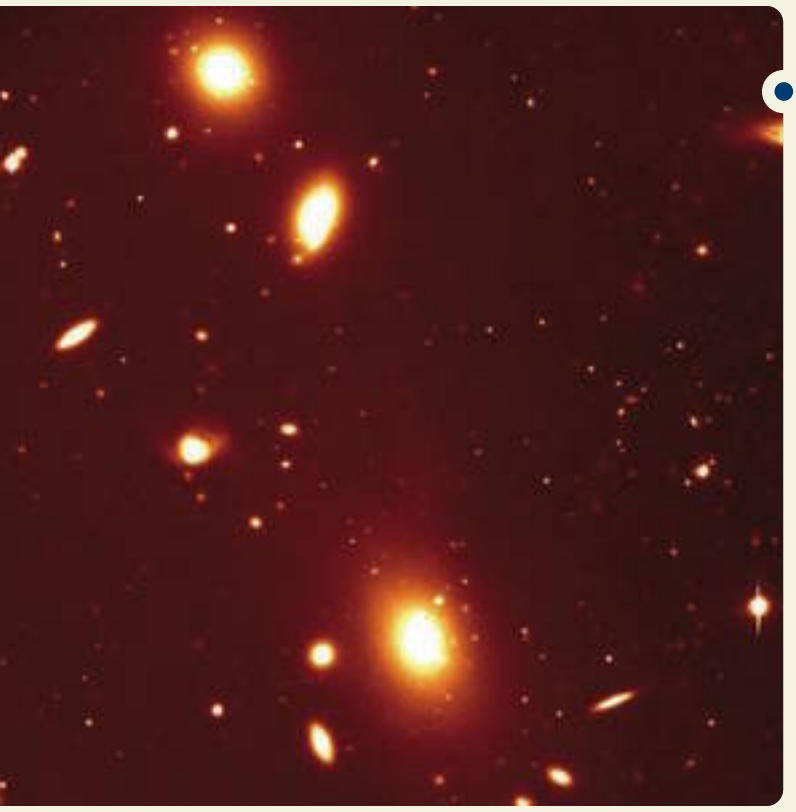


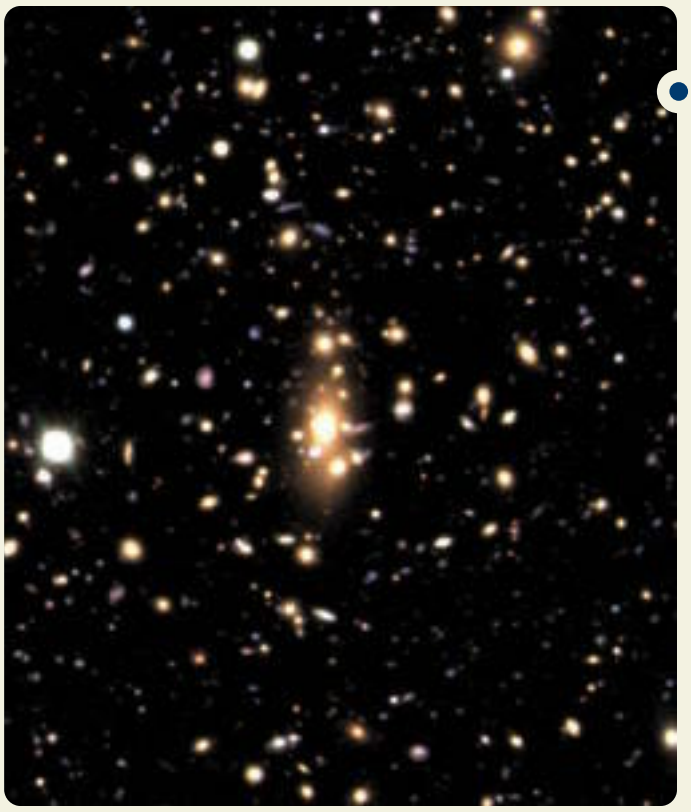


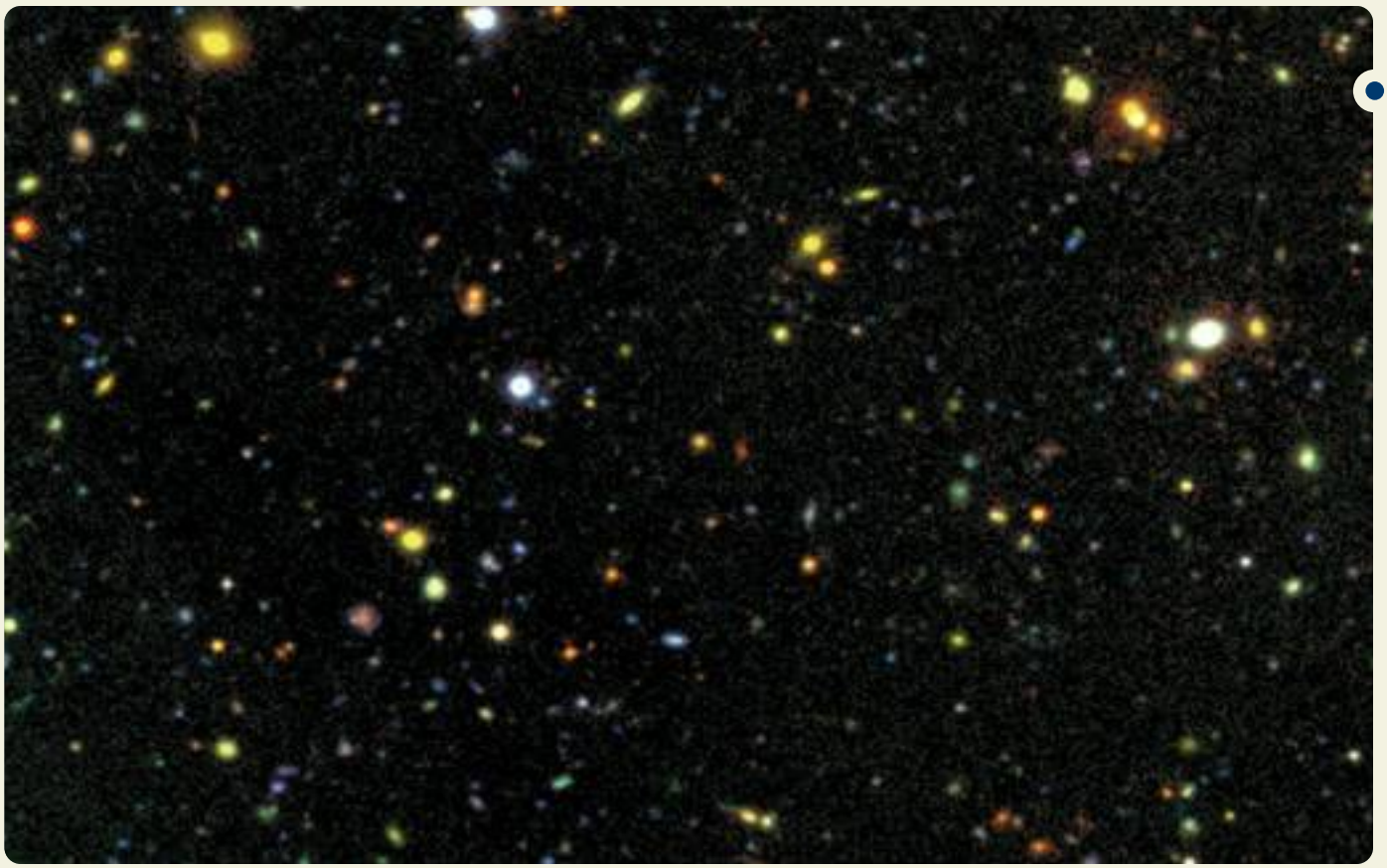
Top left, **HUBBLE ULTRA DEEP FIELD,** visible and infrared light, 2003–2004 /// STScI

Top right, **HUBBLE ULTRA DEEP FIELD,** visible and infrared light, 2003–2004 /// STScI

Above, **DISTANT GALAXY CLUSTER** EIS0046–2930 in Sculptor, visible and infrared light, 1998 /// ESO







Top left, **DISTANT GALAXY CLUSTER** ACO 3341 in Columba, infrared light, 2002 /// ESO

Top right, **CORE OF DISTANT GALAXY CLUSTER** MS 1008.1–1224 in Hydra, visible and infrared light, 1999 /// ESO

Above, **DEEP FIELD NEAR QUASAR Q0103–260** in Sculptor, visible and infrared light, 1998 /// ESO

Above, **A VERY DISTANT OBJECT** (curving line) lensed by a foreground galaxy cluster, Abell 370, in Cetus, visible and infrared light, 1998 /// ESO

Unveiling the DARK

A new ground-based telescope promises to nail down the distribution of dark matter. /// BY RAY VILLARD

Virtually all our understanding of the universe is built on "pedestals of light," the bright objects that fill the night sky. Yet the glow of gas, stars, and galaxies has skewed our view of the universe in much the same way that someone flying at night can only guess at the topography of the ground below from seeing the lights of towns and cities.

Astronomers now realize those light pedestals are embedded in an invisible fabric called dark matter, which accounts for nearly one fourth of all the stuff in the universe. Add to that the even stranger realization that a repulsive form of gravity (or antigravity), dubbed dark energy, may be pushing galaxies apart while accounting for nearly three quarters of the universe's energy content. Visible light comes from ordinary matter, which makes up only about 4 percent of the universe's total mass-energy content. Simply put, there's a lot out there we can't see.

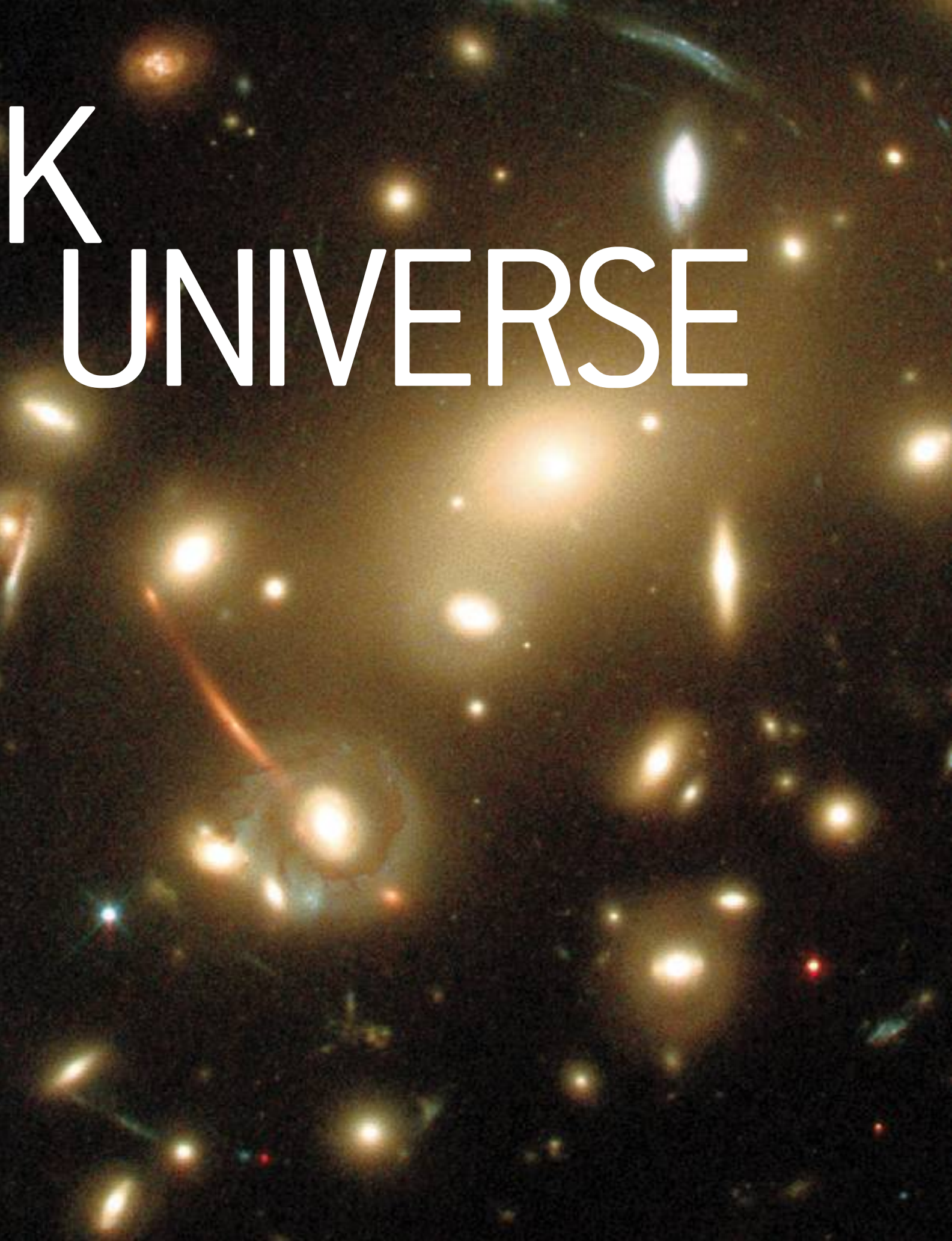
Despite the exquisite resolution of the Hubble Space Telescope or the sensitivity of the twin Keck telescopes, today's powerful observatories can barely scratch the surface when it comes to probing this unseen universe. For centuries, starlight was virtually the only game in astronomy, but it's now clear we'll never fathom the architecture of the universe by studying starlight alone.

This calls for an innovative and radically new dark-matter probe — the proposed Large-aperture Synoptic Survey Telescope (LSST). The LSST won't look for dark matter particles directly — whatever they are — but it will infer the presence of dark matter by a phenomenon called gravitational lensing. Scientists will be able to calculate the mass and distribution of dark matter by seeing how it deflects light emitted by luminous objects.

The LSST is a follow-on to the highly successful Sloan Digital Sky Survey, which ultimately will map one-quarter of the entire sky, determining the positions and brightnesses of more than 100 million celestial objects and distances to more than a million galaxies and quasars. The LSST will

DARK MATTER PERVADES THE UNIVERSE, as in galaxy cluster Abell 2218, where its gravity distorts the light of more distant objects. The LSST will map the distribution of dark matter in the universe in unprecedented detail. NASA, ESA, ANDREW FRUCHTER (STScI), AND THE ERO TEAM (STScI + ST-ECF)

Updated from the November 2002 issue of *Astronomy*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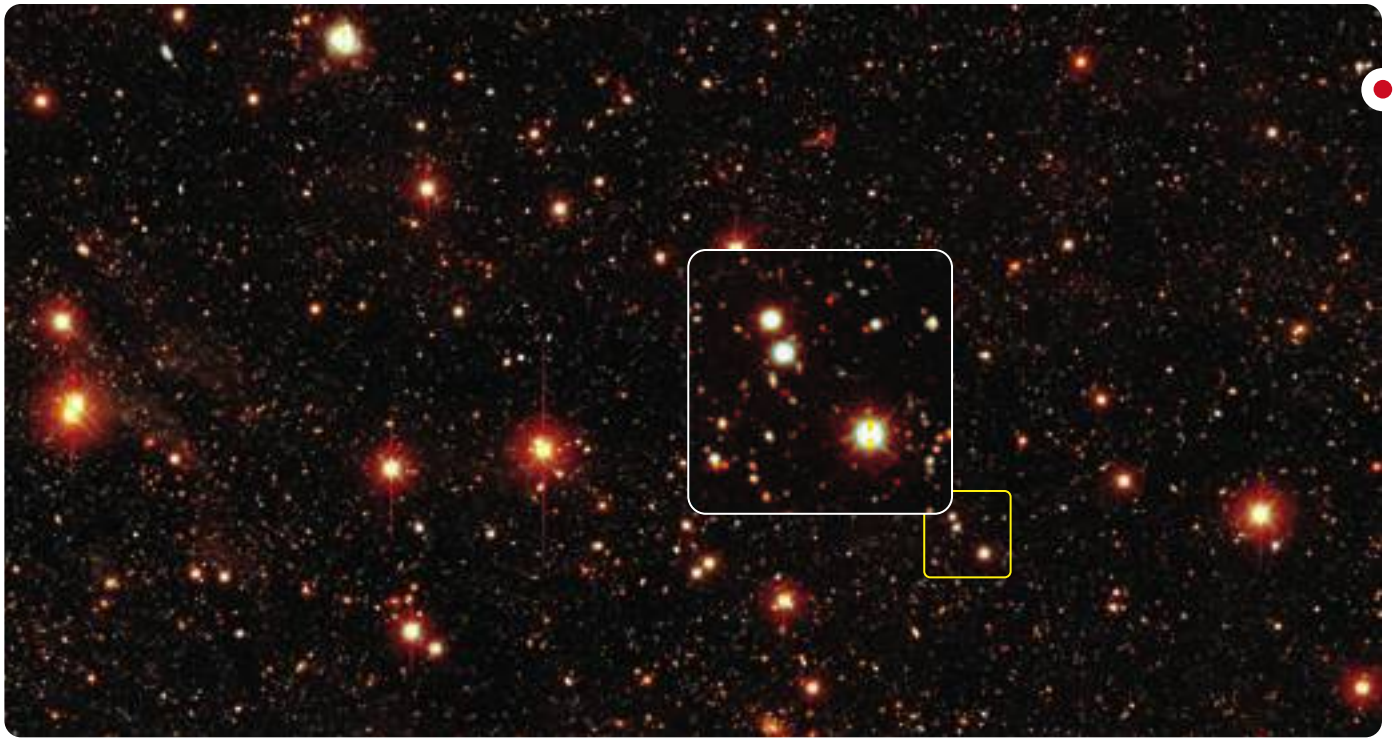


THE NATIONAL OPTICAL ASTRONOMY OBSERVATORY'S DEEP LENS SURVEY shows incredible detail, but it will pale in comparison with what the Large-aperture Synoptic Survey Telescope has in store. DEEP LENS SURVEY AND NOAO

also complement other proposed cosmology missions such as the Supernova Acceleration Probe (SNAP). Veteran dark-matter sleuth Tony Tyson of Bell Laboratories/Lucent Technologies and master mirror-maker Roger Angel of the University of Arizona are part of the team of astronomers and physicists trying to achieve "first light" for the new observatory by 2011.

The telescope they're lobbying for will be a powerful and versatile instrument that will do what a few years ago would have been deemed impossible — map almost the entire sky down to 24th magnitude every several nights. That's a threshold so faint that the nightly inventory will number 200 million objects.

"There will be about 30,000 galaxies and 3,000 stars per square degree of sky — not counting tens of thousands of asteroids," says Tyson. "We will repeat these exposures at least every 25 seconds through the night, tiling the sky with 7-square-degree patches."

Over a significant amount of time, a total of 14,000 square degrees will be covered with multiple exposures to build an image down to 27th magnitude, which corresponds to 600,000 galaxies per square degree. The resulting image compilation and photometric catalogs will contain roughly 10 billion objects: galaxies, stars, brown dwarfs, comets, asteroids, and energetic explosions in the early universe.

This will allow the LSST to map out the huge dark-matter structures that form a ghostly cobweb across the universe. Acting as a movie camera, it will document key phenomena in a transient universe — one crackling, popping, and bubbling with titanic explosions, stellar flares, and other outbursts.

Closer to home, the LSST will also keep tabs on the solar system's silent denizens of the night. It will chart the orbits of almost all asteroids and comets that pose a threat to Earth. The LSST will do a census of the Kuiper Belt, the solar system's last unexplored frontier.

The huge "discovery space" available to the LSST — only marginally accessible to today's telescopes — is guaranteed to make deep inroads into everything from probing the underpinning of the universe's origin and evolution to doing a complete inventory of our solar system. When opening a vast frontier like this, it's a sure bet the telescope will deliver profound and unexpected discoveries that reinforce the emerging view that the universe is a far stranger place than we ever imagined.

Big job, big scope

The telescope needed to accomplish such a herculean task must be herculean too. It requires an innovative optical design, a state-of-the-art "supercamera," and an extremely ambitious computer system to sort and archive the flood of data that will exceed the volume of everything collected by the present generation of telescopes put together.

The LSST's wide field of view requires a short 10-meter focal length. The center of gravity is in the middle of the squat telescope so it can quickly pivot around a small turning radius inside a relatively small housing. To control the wide view, the telescope has three sets of mirrors. The large 8.4-meter primary mirror is a twin of the mirrors on the University of Arizona's Large Binocular Telescope.

Relative to other 8-meter-class telescopes, the LSST will be like a motor-driven handheld camera compared with a portrait-studio, tripod-mounted camera. To survey the sky, the telescope has to be agile enough to re-point by 3 degrees in merely five seconds.

The novel optical design will allow LSST to go very deep and wide. The telescope will gaze at a whopping 4,000 square degrees of sky per night, approximately one hundred times the area of the bowl of the Big Dipper.

Ray Villard *is public information officer at the Space Telescope Science Institute in Baltimore, Maryland.*

THE LSST WILL DETECT THOUSANDS OF DISTANT SUPERNOVAE like this one (arrow) in the Hubble Deep Field, helping to pin down the accelerating expansion rate of the universe. NASA AND ADAM RIESS (STScI)

The LSST will need to be located at a prime ground-observing site with the best possible weather. A site in the mountains of Chile is under consideration. Ideally, a telescope in the Northern Hemisphere could combine with one in the Southern Hemisphere to cover the entire celestial sphere. Being on the ground rather than in space will keep construction costs to approximately $120 million, although seeing conditions will not be as optimal.

In a 20-second snapshot, the fast optics will plunge deep into the cosmos to capture faint stars and galaxies the size of our Milky Way located halfway across the universe.

The tertiary mirror will feed starlight from its 3°-wide field of view to a 2-foot mosaic of dozens of optical detectors totaling 2 gigapixels. Starting a new exposure of a different part of the sky every 30 seconds, the LSST's camera will pour out imaging data at 500 megabytes per second. The torrent of data from the LSST is unprecedented for any current optical telescope but comparable to the data rates found in particle physics experiments.

Software must process the data stream in close to real time in order to automatically detect and classify both variable and moving objects. Results will be placed in an archive that can be readily retrieved by the astronomical community.

Mapping the shadow universe

Despite today's vast array of magnificent ground- and space-based telescopes, it is humbling to realize we can't see the very substance that dominates the mass of the universe and controls the development of its structure. Over billions of years, and working in ways no one truly understands, dark matter established the underlying foundation for assembling ordinary matter into galaxies, stars, planets, and life.

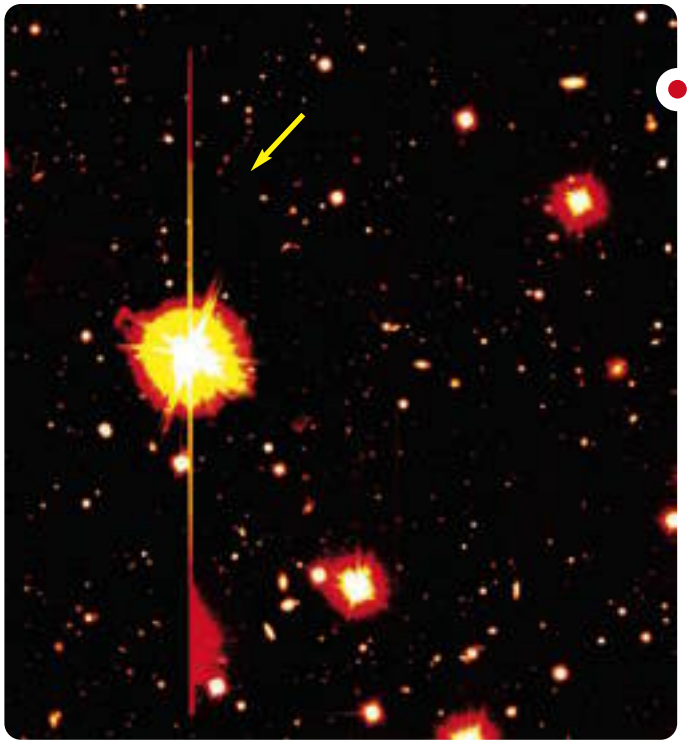
The gravitational effects of dark matter give the universe a distorted "shower curtain" appearance caused by gravitational lensing. Albert Einstein first predicted this phenomenon when he theorized that gravity warps space. This means light can be deflected by gravity as it crosses space, like a golf ball rolling over uneven turf.

But you really don't appreciate how distorting a transparent shower curtain can be until someone stands behind it and you see how much the person's appearance changes. Likewise, the light from billions of distant galaxies provides background wallpaper that is noticeably distorted by dark matter in the foreground. The LSST will need optimum observing conditions to measure the "shear effect" on galaxies, a measure of how much their images are stretched by lensing.

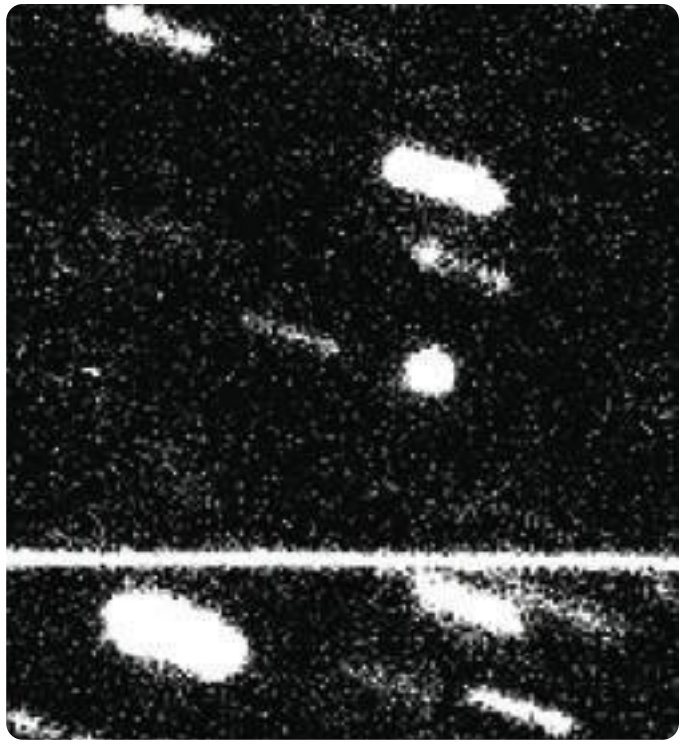
The LSST will make a three-dimensional map of this dark matter by measuring distances to both the gravitationally lensed galaxies and the foreground clusters of mass that are doing the lensing. Distances to the background galaxies will be measured based on their color. This technique, called photometric redshift, is used increasingly as a substitute for the traditional spectroscopy that makes an unequivocal measurement of an object's cosmological redshift. But many distant targets are simply too faint for this tried-and-true technique to be used exclusively anymore.

The LSST's mapping of dark matter will measure both the geometry of the universe and the growth rate of its structure. The amount of distortion in the shapes of galaxies will help fine-tune the measure of the universe's balance of energy and matter. Dark energy inhibits the growth of structure, so the LSST will help determine the nature of the elusive dark energy that is now pushing the universe apart.

The mapping will also identify galaxy clusters at great distances and tell us how quickly large-scale structures froze out of the dark-matter web in the early universe. Gravitational lensing can also split images of distant quasars, and the frequency of this effect yields clues as to how gravity curves space.



THE LSST WILL EXCEL AT FINDING OBJECTS that flare up in the darkness of space, as this gamma-ray burst (arrow) did in January 2000, when it surged energy into deep space. ESO



ASTRONOMERS HAVE DISCOVERED about 1,000 Kuiper Belt Objects, including the round smudge of 1996 TO_{66} seen here. The LSST should find at least 10,000 of these distant solar system objects. ESO

The LSST can play a role in probing dark energy — the dominant component of the universe's energy density — by searching for supernovae. Supernovae present a window into the distant past and offer the best way to measure how the universe's expansion has changed over time.

Hubble Space Telescope astronomers got lucky in 2000 with their chance discovery of a distant supernova. It was so far away that it yielded the long-awaited evidence that the universe once was slowing down but is now speeding up thanks to the repulsive influence of dark energy.

If the universe were expanding at a steady rate, the light from distant supernovae would dim at a predictable pace depending on their distance from Earth. If the supernova light is brighter than predicted, the universe has been expanding slower than expected since the time the supernova exploded. If the light is fainter than predicted, the universe has been expanding faster than expected since the time the supernova exploded.

But many more remote supernovae must be found to help astronomers understand the nature of the dark energy that kicked the universe into high gear 7 billion or so years ago. Ground-based surveys have netted fewer than 300 supernovae per year. The LSST will complement the ambitious supernova survey planned by the proposed SNAP mission that is expected to find more than 1,000 supernovae at the critical epoch when cosmic acceleration began. SNAP will provide a deep "pencil-beam" view of the sky; the LSST's designers predict that LSST's wide view and depth will capture 200,000 moderately distant supernovae each year. By training their eyes on supernovae, LSST astronomers hope to determine the exact amount of expansive push dark energy exerts as compared to the exact amount of gravitational resistance provided by dark matter.

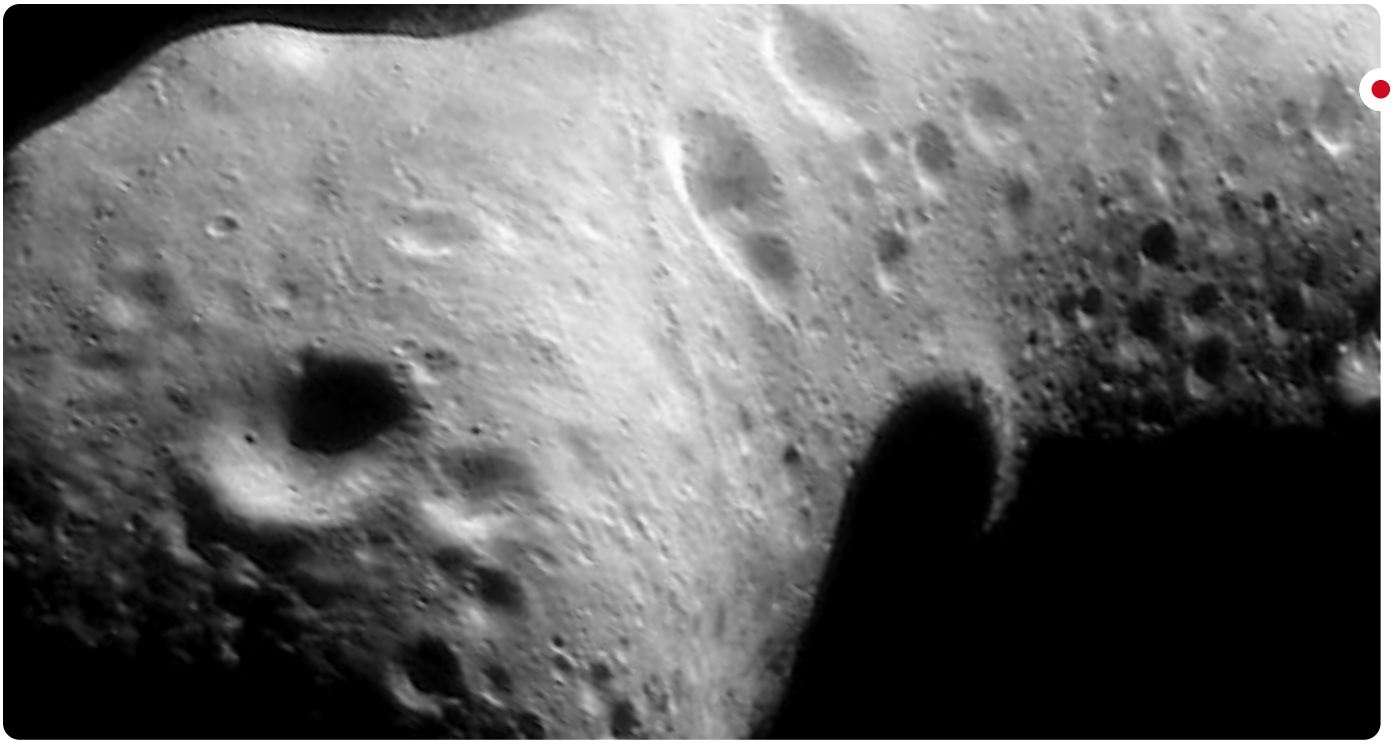
The LSST will also open a new window into the early, violent universe. Far away and long ago, galaxies collided more frequently than now and stars were born in firestorms of creation triggered by those collisions. Astronomers started getting hints of this violence in the 1970s, when defense satellites led to the discovery of gamma-ray bursts (GRBs). Unleashing 100 times the power of a supernova, these titanic gamma-ray explosions happen about once per day somewhere in the sky. Most sources reside billions of light-years away. With luck, the telescope's wide view will pick up fainter GRBs popping off like firecrackers. The telescope will record their color and precise brightness and track their fading afterglows.

What's new?

GRBs form just the tip of the iceberg. A staggering variety of astronomical phenomena come and go like fireflies in the night. Collectively called transient events, they include outbursts from black holes powering active galaxies and quasars, variable stars, stellar flares, and microlensing events where a star momentarily brightens when a dim foreground object passes in front of it.

The LSST promises to yield new insights into our own galaxy by compiling a huge database of variable stars of many types, such as eclipsing binaries. There is a tantalizing opportunity to find extrasolar planets by witnessing rare transit events, where a planet tracks across the face of its parent star. Astronomers also anticipate the LSST will turn up previously unknown objects and phenomena.

The LSST's wide field and sensitivity are not just for perusing the distant universe. Much closer to home, at the frigid, outer fringes of our solar system, perhaps billions of faint small bodies travel the dim highways of the Kuiper Belt. Discovery of inhabitants in this vast, icy, debris yard beyond Neptune has climbed rapidly in the past few years. About 1,000 of these Kuiper Belt Objects (KBOs) have been found so far, including a new population of



THE LSST WILL COMPLETE THE SURVEY of near-Earth objects larger than a football field across. Although typically much smaller than asteroid Eros, seen up close in this image from the NEAR-Shoemaker spacecraft, these objects pose a significant threat to Earth. The impact of an object much smaller than Eros would create a regional catastrophe far larger than any recently experienced on the planet. NASA/JHUAPL

binary KBOs, whose evolution and dynamics are mysterious.

Information on the Kuiper Belt will help astronomers understand the origin and evolution of our solar system, while shedding light on planetary systems around other stars. But astronomers have barely scratched the surface. The LSST will carry out a census of the Kuiper population by discovering more than 10,000 KBOs. With such a large statistical sample, astronomers will have a grasp on one of the least-known regions of our solar system.

Studies of extrasolar planetary systems have yielded startling evidence that some giant planets have migrated — a process that may have happened in our solar system as well. The orbits of KBOs are the only fossil records of this activity. These orbits hold clues as to how bodies were shuffled around during the more raucous days of the early solar system. Because many KBOs (including Pluto) are in resonance orbits with Neptune, they can be used to measure how Neptune ejected mass from the solar system.

Dusty disks observed around other stars are no doubt replenished by collisions among Kuiper Belt-type objects. This seems common among young stars and may offer fundamental clues about the birth of planetary systems. Ironically, less is known about the disk of dust encircling our own solar system than those seen around other stars. And we know just as little about the small and dim objects orbiting beyond Neptune.

The LSST will be an invaluable tool for finding asteroids and comets zipping perilously close to Earth — collectively called Near-Earth Objects (NEOs). Astronomers estimate about 2,000 half-mile-wide (1-kilometer-wide) asteroids cross our orbit. But the LSST's wide and deep view, plus its observation frequency, will allow astronomers to catalog thousands of NEOs (including dim near-Earth comets) as small as a football field.

Although not big enough to cause a global catastrophe, objects 500 feet (150 meters) across should not be overlooked. A small NEO could flatten a city with the energy equivalent of a 1,000-megaton explosion. Within ten years, the LSST could catalog 90 percent of asteroids with a diameter of 800 feet (250m) or bigger.

Sky patrol

The LSST will operate differently than most large telescopes. Rather than being used by individuals or groups carrying out more specialized observation programs, it will observe a preprogrammed series of fields, effectively imaging 10,000 degrees of sky every four nights.

The whole-sky images, built up over time to extremely faint levels, will provide critical support for follow-up research at a broad range of observatories. But the LSST's repeated imaging of each patch of sky means that science also can be done purely within the telescope's own database. Researchers, in other words, will not be dependent on follow-up observations from other telescopes.

All told, the LSST is expected to gather a mountain of data — 10 million gigabytes — and storing it in an accessible form will pose a huge technical challenge. The LSST archive will be the biggest database feeding into the Virtual Observatory, an ambitious plan to allow astronomers to tap into the major astronomical databases available today simultaneously.

No doubt, the LSST will be used for research projects undreamed of by its originators. Those efforts — which cannot be spelled out upfront or written into grant proposals — constitute a big part of the project's rationale.

"We are driven to build the LSST facility by what we know it can tell us about our universe," says Tyson. "But the biggest rewards may come from what we cannot predict."

Moving ri

The accelerating universe holds clues to dark energy, the Big Bang, and the ultimate beauty of nature. /// BY MARIO LIVIO

On a cold day in March 1998, the universe was knocked on its head. That day, Adam Riess, currently at the Space Telescope Science Institute, submitted a paper on behalf of the High-z Supernova Team that concluded the universe's expansion is accelerating. Instead of slowing down, as would be expected from the fact that cosmic expansion occurs against the gravitational pull of all matter within the universe, the cosmos is speeding up, as if propelled by some repulsive force associated with a mysterious "dark energy." The High-z team, which was led by Brian Schmidt of Mount Stromlo Observatory, was not alone in this discovery. A second team, led by Saul Perlmutter of Lawrence Berkeley National Laboratory, also found evidence — which has since been corroborated many times over — that the expansion of the universe is accelerating.

Updated from the July 2002 issue of *Astronomy*

DO WE UNDERSTAND GALAXIES LIKE SCULPTOR'S NGC 253? The expansion of the universe appears to be speeding up as time goes on, pulled by a mysterious force associated with a "dark energy." The evidence for an accelerating cosmos comes from observations of supernovae in distant galaxies, as well as density differences in the cosmic microwave background radiation, the echo of the Big Bang. JEAN-CHARLES CUILLANDRE, CFHT

ght along

The idea that a repulsive force acts on the universe is startling, but hardly new. In 1917, when Albert Einstein first tried to apply his theory of general relativity to the entire cosmos, he had to introduce this kind of force to keep the universe static. At the time, Einstein wasn't aware of the fact that the universe is expanding, so he introduced a repulsive force at large distances — the cosmological constant — to which he assigned an arbitrary number. This fudge factor was brought into relativity to support the universe against its own weight. Things changed when Edwin Hubble arrived on the scene. Some time after Hubble discovered the expansion of the universe in 1931, Einstein removed what appeared to be an unnecessary complication from his equations, calling it his "biggest blunder."

Taking a dusty test

So exactly how do astronomers know that the universe's expansion is accelerating? The two teams looked at Type Ia supernovae at very large distances (that is, high redshifts). The tremendous explosions from Type Ia supernovae are catastrophic thermonuclear explosions of white dwarf stars that occur when the stars reach their maximum possible mass — the so-called Chandrasekhar limit of 1.4 solar masses. Two characteristics of these explosions make Type Ia supernovae excellent gauges of distance, or "standard candles." First, the brightness of these explosions is nearly constant. Second, the small deviations from constancy are also well known — the brighter the supernova, the slower it declines in brightness. Thus astronomers can use them to determine cosmic distances. The 1998 observations showed that very distant supernovae, those with redshifts of 0.5 and higher, appeared some 0.3 magnitude dimmer than expected at their distances. In other words, these supernovae were farther away than expected and, therefore, the universe's expansion rate had to be speeding up for the supernovae to reach larger distances.

The first skeptics wondered whether the 1998 observations might be tainted. For example, was it possible that the supernovae appeared so faint because of obscuring dust lying between us and them? After all, as the saying goes, extraordinary claims require extraordinary proof. In 2001, however, Riess and his colleagues took a big step toward showing that alternative explanations like dust absorption do not explain the faintness. Using Hubble Space Telescope observations of the Hubble Deep Field, the deepest exposure ever made in visible or ultraviolet wavelengths, the group showed that Supernova 1997ff, which lies in the field, is the most distant Type Ia supernova known. Its amazingly high redshift of 1.7, which corresponds to a whopping 10.2 billion years ago, offers astronomers a unique opportunity to test the idea that dust is obscuring the observations.

The idea behind the test is simple. Even in a universe that's currently accelerating, if you look into the distant past, you're bound to find an era when the universe was decelerating. When the universe was very small, gravity dominated the dynamics of the cosmos, and the expansion was slowed down by gravity's pull. Only in the last few billion years did the matter density of the universe dip below the density associated with dark energy, causing the expansion of the universe to speed up. Because of this, observations of supernovae with redshifts greater than 0.8 can distinguish between

GRAVITATIONAL LENS ARCS SWIRL through the galaxy cluster CL2244–02 (top), a composite image taken with the Very Large Telescope in Chile. The southern galaxy ESO 269–57 (bottom) displays a strong ringlike structure and well-defined spiral arms. ESO

obscuration by dust and the real thing — acceleration. If supernovae are dimmed by dust, then more distant ones should appear fainter and fainter, as their light needs to pass through ever-increasing amounts of dust.

The accelerating universe

If, on the other hand, we live in an accelerating universe, then supernovae at very high redshifts (seen when the universe was still decelerating) should look brighter than expected for their distance. Indeed, the observations of supernova 1997ff show it to be brighter than anticipated, which is consistent with a cosmic acceleration scenario rather than a dust obscuration one. Supernova observations also suggest we live in a universe in which matter of all forms, including dark matter, provides only about 27 percent of the density that makes the universe geometrically flat. The other 73 percent of the density comes from dark energy, whatever that is. Astronomers use the Greek letter omega, Ω, to denote the cosmic density: An Ω of 1.0 implies a geometrically flat universe. If Ω is greater than 1.0, the universe would be closed, corresponding to a geometry like that of a sphere. If Ω is smaller than 1.0, then the universe is open with a geometry like that of a saddle. A flat universe with a dark energy contribution of 73 percent is expected to expand forever, at an ever-increasing rate.

Another bit of evidence strongly suggests that the universe is speeding up. For years, astronomers have studied the Cosmic Microwave Background (CMB) radiation. Measurements of the anisotropy (or unevenness) of the CMB radiation show the temperature difference between two points on the sky is greatest when those points are about 1° apart. Why is this important? It's a reflection of the geometry of the universe. The CMB radiation is coming from the "surface" on which radiation particles, or photons, last interacted with matter in the early universe, before the universe became transparent. As baryons and leptons — ions and electrons — fell into the gravitational "wells" generated by dark matter, photons pushed against them, which produced acoustic oscillations. The waves generated by this process caused undulations in the surface from which the CMB radiation was emitted, creating fluctuations in the temperature of the universe.

In the same way that sounds produced on the head of a drum depend on the drum's size and geometry, the longest wavelength that had time to oscillate in the CMB depended on the geometry of the universe, which depended in turn on the value of Ω. In particular, the maximum temperature difference for points on the sky 1° apart corresponds to a flat universe and an Ω of 1.0. If Ω is smaller than 1.0, the differences in temperatures are largest between points separated by less than 1°. It's similar to the experiment you can perform by holding a penny close to your eye, where it covers a wider angle in your field of view than if you hold it farther away. A number of experiments analyzing the CMB — the Wilkinson Microwave Anisotropy Probe in particular — suggest the density of matter in all forms is about 27 percent of the critical value, and that dark energy represents 73 percent.

TIGHTLY WRAPPED SPIRAL ARMS characterize the spiral galaxy M63 in Canes Venatici (top). A weirdly curving dust band bends its way alongside the edge-on galaxy ESO 510–G13 (center). The knotty spiral galaxy IC 4248 (bottom) lies at a distance of 210 million light-years. NASA/STScI AND ESO

/// IS THERE BEAUTY IN NATURE?

What do physicists mean when they label a certain theory as beautiful? As defined by Webster, beauty is the quality that "makes an object seem pleasing or satisfying in a certain way." While this may be a suitable definition for a work of art, physicists don't quite mean the same thing.

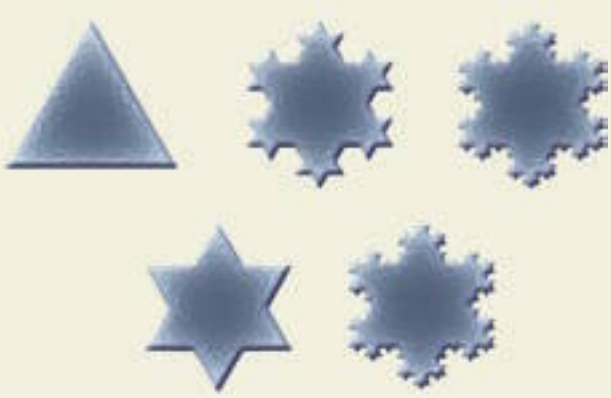
The two main elements of beautiful theories are symmetry and simplicity. By "symmetry" I don't mean the symmetry of shapes or objects, like the left-right symmetry of the human face. I mean symmetry in the laws of physics themselves, such as the fact that they don't change from place to place in the universe. This is what makes astronomy and astrophysics possible. We can use the same laws of electromagnetism deduced from laboratory experiments on Earth to study a galaxy a billion light-years away. The laws of physics are also symmetrical under rotation, meaning that physics has no preferred direction in space.

Separating the symmetry of shapes from that of laws is best exemplified by looking at planetary orbits. From ancient Greece to Galileo's time, astronomers had assumed planetary orbits must be circular because of a circle's inherent symmetry. Consequently, when Kepler discovered that orbits were elliptical, even Galileo refused to accept the finding.

Not having Newton's law of gravitation at his disposal, Galileo didn't recognize that symmetry under rotation is a property of that law and not of the shape of the orbit. In other words, the orbits can be, and indeed are, ellipses, but the symmetry of the law of gravitation under rotation implies that the ellipses are allowed to have any orientation in space.

When I speak of simplicity, I really mean reductionism. The goal of physics has always been to explain the wealth of phenomena we observe in nature by a relatively small number of fundamental laws. Consider star birth in gas clouds, the deaths of stars like the Sun, and the collision of two galaxies. All these processes involve four basic interactions: gravity, electromagnetism, and the two nuclear forces.

"Geometry, which before the origin of things was coeternal with the divine mind," Kepler wrote, "supplied God with patterns for the creation of the world." Accordingly, he wrote an entire treatise on "The Six-Cornered Snowflake," investigating why snowflakes have a six-fold symmetry. This curiosity and inquisitiveness forms the backbone of science.



FRACTAL BEAUTY reveals itself in many forms — in the crystal shapes of snowflakes, for example. A simple triangle can be repeated thematically to produce very complex fractal shapes that reflect a six-fold symmetry that is clearly beautiful. *ASTRONOMY:* ROEN KELLY

Astronomers know the dark energy component of the energy density did not interfere with the formation of the structures we observe today in the universe, meaning it was less important in the past. Based on this, one can show that dark energy has a negative pressure. However, in general relativity, gravity acts proportionally to the sum of the matter density and three times the pressure. For a sufficiently negative pressure, therefore, gravity becomes a repulsive force, leading to the acceleration of the universe's expansion.

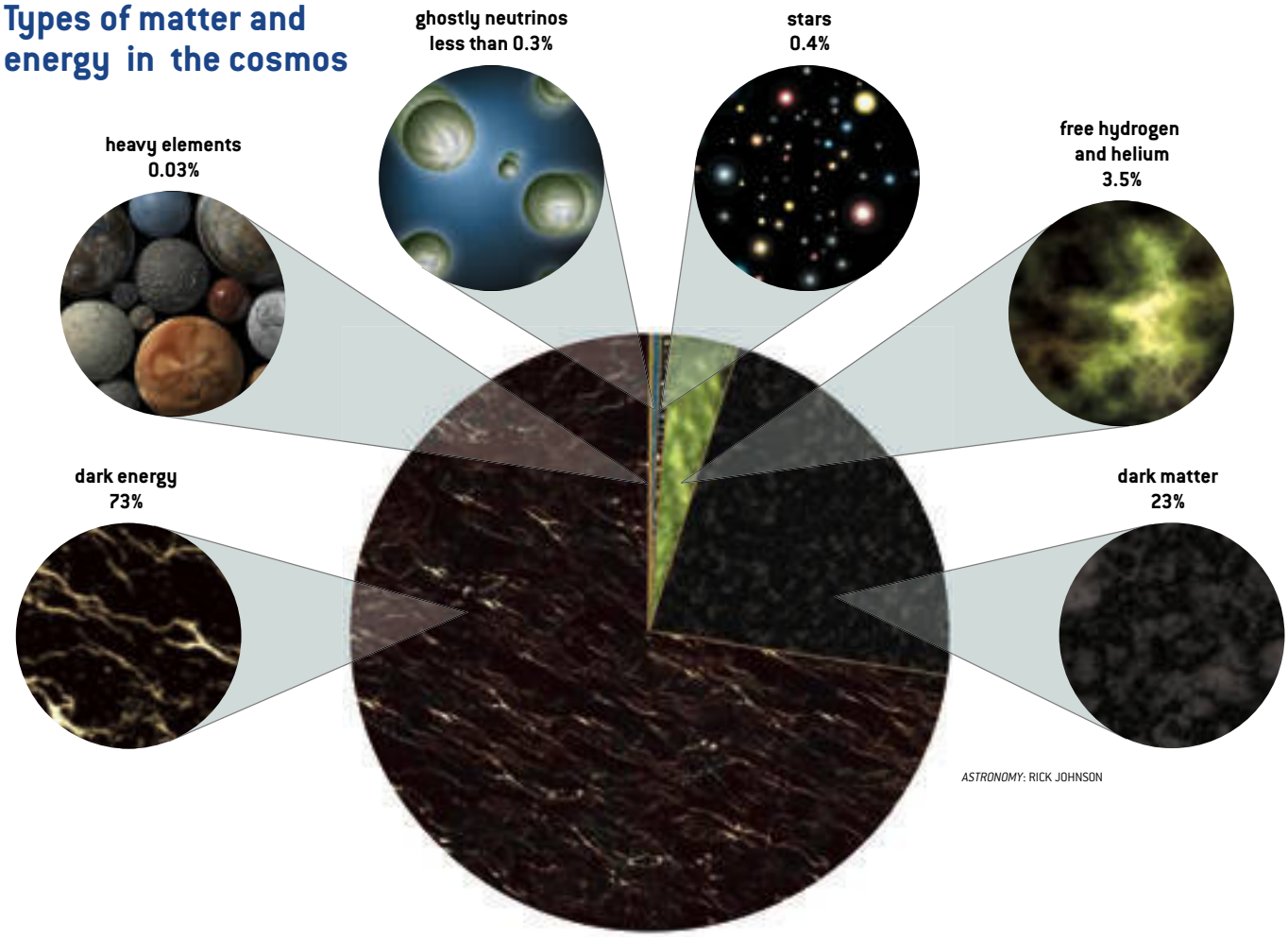
Beauty in distress?

Observations of both distant supernovae and the CMB strongly suggest that we live in an accelerating universe whose energy density is dominated by some mysterious form of dark energy. There's a problem with this finding, however. The model of the universe it implies is preposterously complex. Physicists normally assume fundamental theories of the universe must be "beautiful." Successful theories, in other words, are based on symmetry and simplicity (see "Is there beauty in nature?," left). A physicist's aesthetic sensibility is really an important research tool that can guide him or her to a correct hypothesis. The best example of this is Einstein's general relativity, which in his own words was "beautiful beyond comparison."

In general relativity, the underlying symmetry comes from the idea that all frames of reference are equal. Regardless of whether we live on a rocket moving through space at a constant speed, on a clump of matter accelerating from an exploding supernova, or on the surface of a rapidly spinning star, the laws of nature look the same.

How does general relativity fit into this theme of symmetry and simplicity? Isn't it notoriously complicated? After all, in 1915, Einstein himself said that "only one colleague [mathematician David Hilbert] has really been able to understand it." Although the equations describing general relativity and their solutions are more complex than Newton's theory of gravitation, the central idea is actually much simpler. Instead of being a mysterious force that acts across space, gravity merely reflects the geometry of space-time. In the same way a heavy bowling ball resting on a tight rubber mat would cause it to sag, every mass warps space-time in its vicinity. The planets move along curved orbits because they follow the most natural paths in the curved space-time produced by the Sun. Similarly, an airplane flying from the United States to Europe follows a great circle along Earth's surface.

So where's the symmetry and simplicity in the new model of the cosmos? The values of the different energy densities appear to be anything but simple. In fact, the inferred value for dark energy, 73 percent, is bizarre. The most "natural" value for the energy density should have come from the so-called Planck Era, when the universe was 10^{-43} seconds old. But that value is some 123 orders of magnitude larger than the one that astronomers observe — a huge discrepancy even by astronomical standards. When adjustments are made to accommodate the principle of supersymmetry, for example, the energy density value is still 55 orders of magnitude too large. Attempts to reconcile this difference by making dark energy evolve over time still require some fine-tuning. It's difficult to accept the notion that somehow the influence of dark energy changed in the recent past. Theories of the universe are usually Copernican — they assume that humans are


Types of matter and energy in the cosmos
ghostly neutrinos less than 0.3%
stars 0.4%
heavy elements 0.03%
free hydrogen and helium 3.5%
dark energy 73%
dark matter 23%
ASTRONOMY: RICK JOHNSON

ordinary observers; they are not graced with some special time or place to make things feasible.

Does this mean we are facing a breakdown of some of our most cherished theories of the universe? Has the centuries-old assumption of a simple, symmetric, Copernican view of the universe reached its limits?

I don't think so. We are probably in the same situation that the famous physicist Isidor Rabi found himself in when he heard about the discovery of the muon. "Who ordered that?" he asked indignantly. Assuming that recent indications of the value of Ω are confirmed, I believe that in time we'll find the current confusion relates to what is really fundamental and what isn't. Galileo was upset by elliptical orbits because he didn't realize the shape and symmetry of the orbits were not fundamental — the symmetry of gravity was. Kepler wrote an entire, outrageously wrong treatise trying to explain the number of planets and sizes of their orbits because he thought those numbers and sizes were fundamental. Before the standard model of particle physics emerged, accelerators were finding scores of so-called elementary particles, most of which now are known to be simply excited states of collections of two or three quarks.

Mario Livio *is head of the Science Division at the Space Telescope Science Institute in Baltimore. He is the author of* The Accelerating Universe *(Wiley, 2000) and* The Golden Ratio *(Doubleday/Broadway, 2002).*

It's quite possible astronomers will eventually realize that the only truly fundamental value is Ω, and that Ω = 1.0 and the universe is flat. This is a direct result of inflation, which has all the hallmarks of a simple, symmetric, and Copernican theory. The existence of a cosmological constant is not inconsistent with the symmetry principle of general relativity, which states the laws of nature should be the same in all frames of reference in space and time.

But other possibilities exist. Alternative theories of gravity have been proposed that rely on extra dimensions to suggest that what we see as dark matter halos may, in fact, reflect the gravitational influence of matter in other, unseen universes. The idea is that while all other interactions are confined to our universe, gravity may be free to travel in a fifth dimension, and thus migrate from one universe to another. While these ideas are highly speculative, perhaps they could be tested by measuring the strength of gravity on very small (submillimeter) scales.

No fewer than five experiments are in the works to test this idea. Experiments at the Large Hadron Collector in Geneva, Switzerland, later this decade also may be able to test these ideas by documenting instances of missing energy — gravitons escaping into a fifth dimension, for example. If these alternative ideas about gravity are confirmed — or if we realize the current density of dark energy is accidental rather than fundamental — it would mean that the beauty of the universe may not be in jeopardy at all. Our understanding of it simply needs to play catch-up.

Will dark energy steal the stars?

Armed with new supercomputer calculations, astronomers probe where cosmic acceleration is taking us. /// BY STEVE NADIS

NASA, HOLLAND FORD (JHU), GARTH ILLINGWORTH (UCO/LICK OBSERVATORY), NARCISO BENITEZ (JHU), MARK CLAMPIN (STScI), GEORGE HARTIG (STScI), THE ACS SCIENCE TEAM, AND ESA

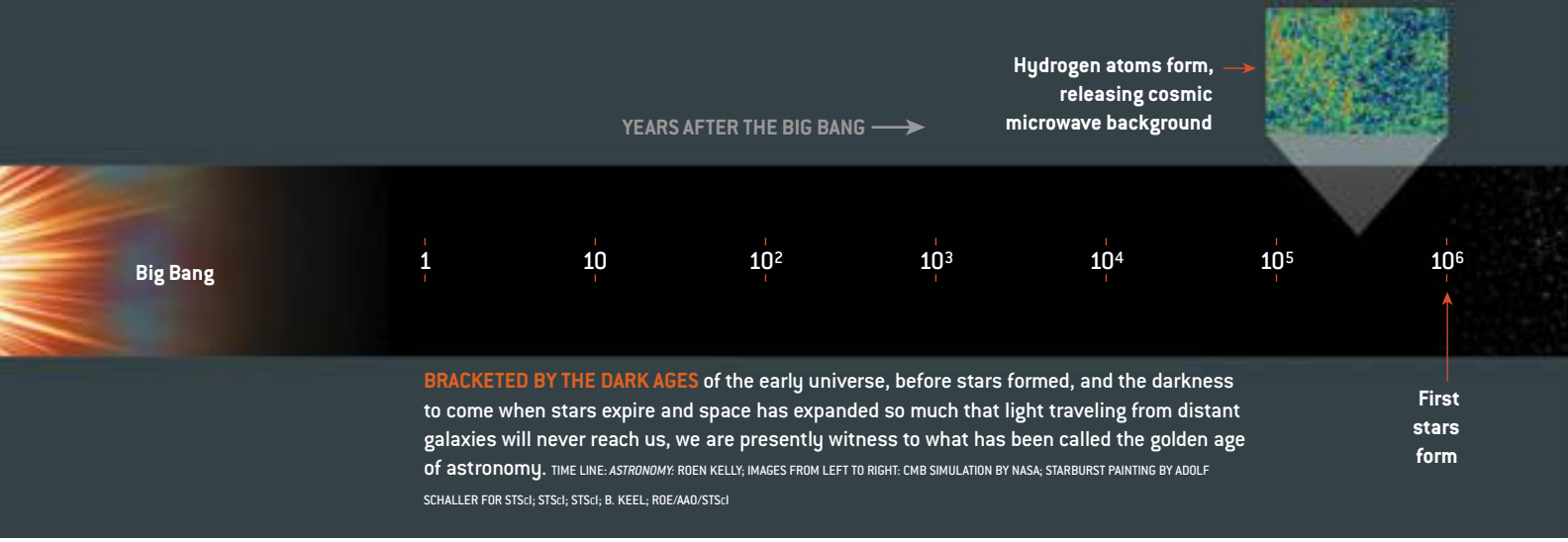
Ever since 1998, when astronomers found evidence that the expansion of the universe is accelerating, with no sign of slowing down, a few practitioners have been trying to determine exactly what this means for both the cosmos and their beloved field. Will astronomy have a future in a universe dominated by dark energy — a mysterious, repulsive form of energy that fills the vacuum of space, counteracting gravity at every turn?

If the prospect sounds ominous, consider this: Dark energy is thought to constitute about 70 percent of the energy in the universe today. But because it seems to be an intrinsic property of space itself, dark energy will grow along with space. When the universe is twice its present age, according to some theorists, dark energy will comprise 97 percent of the total, rendering matter insignificant in the grand scheme of things. So assuming anyone is around tens of billions of years from now to make observations, what will they look at? And, more to the point, will there be anything left to see?

Some clues are emerging from computer simulations by astrophysicists Kentaro Nagamine and Abraham Loeb at the Harvard-Smithsonian Center for Astrophysics (CfA). In about 14 billion years, our Milky Way will merge with the Andromeda Galaxy and other star systems in the Local Group, although gravity will not be strong enough to keep us tied to the Virgo Cluster. One by one, distant galaxies will recede, becoming dimmer until they totally fade away.

To the untrained eye, the night sky then will look similar to what we see today. Sure, there'd be about twice as many stars as a result of the Milky Way–Andromeda merger, and the stars would be spread more evenly as the galaxy becomes more elliptical. The casual observer might not even

Updated from the March 2003 issue of *Astronomy*



BRACKETED BY THE DARK AGES of the early universe, before stars formed, and the darkness to come when stars expire and space has expanded so much that light traveling from distant galaxies will never reach us, we are presently witness to what has been called the golden age of astronomy. TIME LINE: *ASTRONOMY:* ROEN KELLY; IMAGES FROM LEFT TO RIGHT: CMB SIMULATION BY NASA; STARBURST PAINTING BY ADOLF SCHALLER FOR STScI; STScI; STScI; B. KEEL; ROE/AAO/STScI

notice these changes. But in a few more billion years, "the rest of the universe would literally disappear," says Lawrence Krauss, a physicist at Case Western Reserve University who has done calculations with colleague Glenn Starkman on the fate of a universe governed by dark energy.

Other computations that look ahead 100 billion years reveal the web and filamentary structures upon which galaxies congregate eventually get stretched to the breaking point. In place of the familiar cosmic web, we're left with isolated clumps of galaxies separated by unimaginably huge voids.

WHILE DARK ENERGY PUSHES space apart, gravity still wins out locally. This image of NGC 5090 (right) and NGC 5091 shows a pair of interacting galaxies, where 5090 appears to be tidally disrupting 5091. Eventually, the two may merge to make a single, much larger galaxy. Yet in 100 billion years, space will expand so much that nothing beyond this mega-galaxy would be visible to anyone living inside it. ESO

One might wonder what's the point of such exercises. The Sun will grow so large in another billion years that life on Earth will no longer be an option. Assuming we can somehow escape to a hospitable planet or spaceship, why should we concern ourselves with what might happen 100 billion years from now? The answer, in part, is because we can. The laws of physics work in both directions, says Loeb, so "trying to imagine the future is a legitimate and worthwhile endeavor, especially now that we have some robust data about cosmic acceleration."

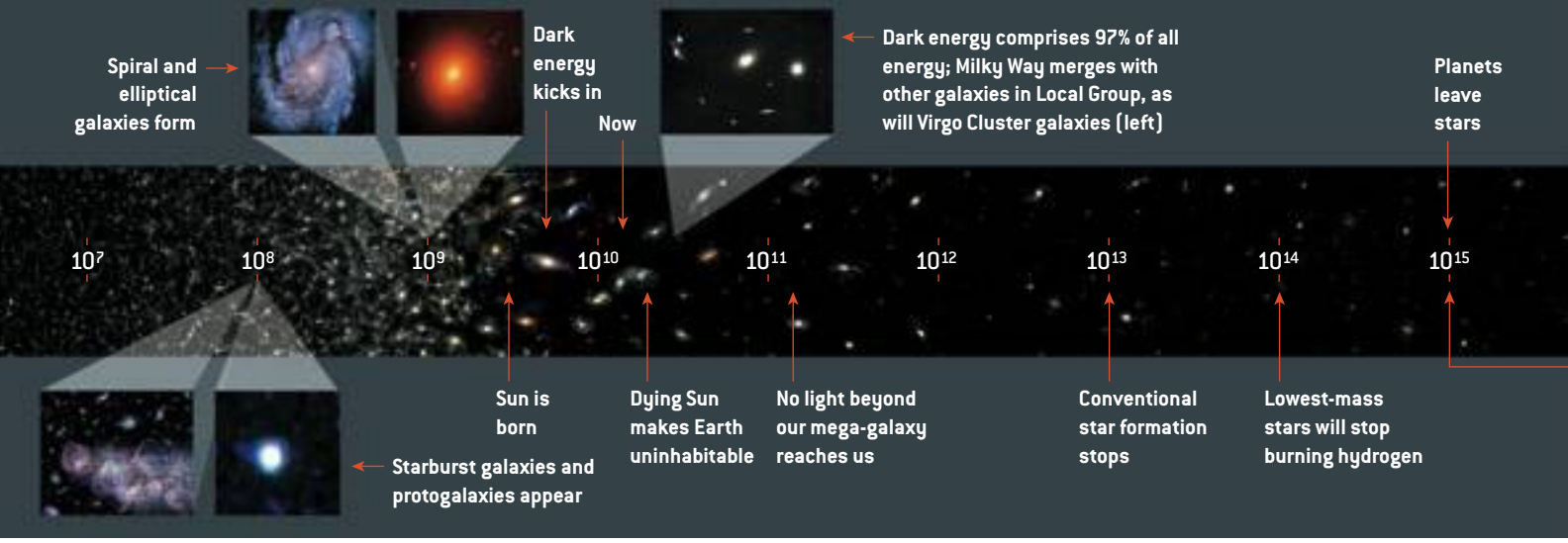
"Most of our colleagues are focused on the past because that's what the sky gives you," adds Gus Evrard, a University of Michigan cosmologist who runs supercomputer simulations with colleagues Fred Adams, Michael Busha, and Risa Wechsler. "One hundred billion years is a ridiculous timescale compared to human lifetimes, which makes the whole project seem fanciful. Yet we think nothing of looking backward 14 billion years and do it all the time. So why not look forward and see what we find out?"

Blinded by the night

What has been learned so far? Calculations by Loeb, as well as by Krauss and Starkman, impose limits on the amount of information we can collect. Until evidence of dark energy became manifest, astronomers assumed the amount of new information available to us was practically boundless. Our horizons were nearly infinite: If we were patient and waited long enough, we could learn more and more about the far reaches of the universe. Now it appears we have to resign ourselves to a future of narrowing possibilities.

That's because in an accelerating universe, the speed of galaxies flying away from each other will overtake the speed of light one day. Photons won't be able to catch up with the rapidly expanding space through which they travel, explains Loeb. As an analogy, he suggests the image of an ant walking on top of an expanding balloon. "If the balloon expands forever at a rate faster than the ant is propagating on its surface," he says, "then the ant will visit only a very small section of the balloon."

Steve Nadis, *who edited this issue, is a contributing editor of* Astronomy *and a freelance writer based in Cambridge, Massachusetts.*



In an accelerating universe, there is a horizon surrounding a galaxy like ours — a distance beyond which light cannot reach us — just as there is an event horizon surrounding a black hole. It is impossible to look beyond our galactic horizon in the same way it is impossible to peer inside a black hole.

Our ultimate fate depends on the true nature of the energy driving the acceleration. If the energy permeating the vacuum has a positive, constant value — a so-called cosmological constant, as Einstein once posited — our horizon is finite. In time, there'll be fewer and fewer interesting things to measure, explains Tom Banks, a physicist at the University of California, Santa Cruz. "We can't say what happens to my friend living on another galaxy once it disappears beyond our horizon, nor can we say what happens to an object once it crosses an event horizon and falls into a black hole." The same, of course, would be true for stargazers confined to different galaxies. As a consequence, knowledge of the universe will be fragmented, with observers studying their own small pieces of the puzzle but forever denied the whole.

> "We think nothing of looking backward 14 billion years and do it all the time. So why not look forward and see what we find out?" — GUS EVRARD

Marooned in the Milky Way

Galaxy clusters like the Local Group, Virgo, and Coma will become entities unto themselves — "island universes" cut off from the rest of the cosmos by the vastness of space. Observers within our new galaxy complex will be confined by our "horizon scale" — a sphere with a radius of 12,600 megaparsecs (or about 40 billion light-years), according to Adams — that is like an impenetrable wall. In 100 billion years, Loeb adds, "We'll be the only galaxy we see in the darkness that surrounds us."

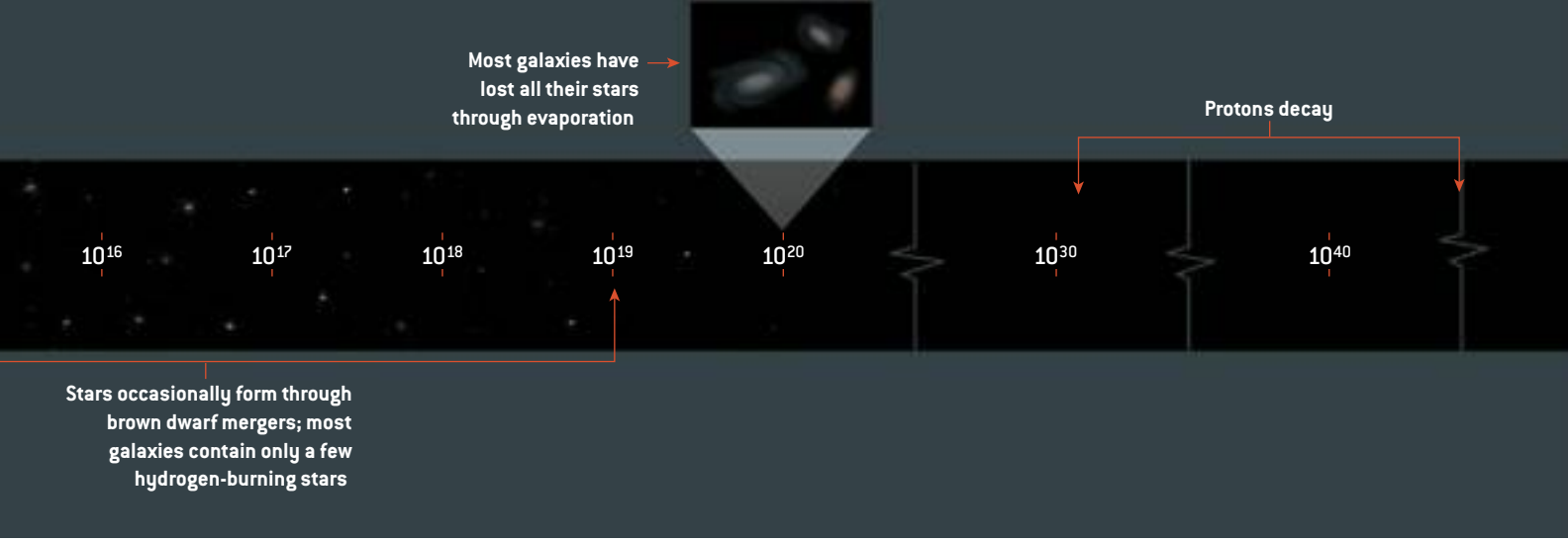
Dark energy, moreover, will inhibit the formation of galaxies, clusters, and superclusters, as the gravitational instabilities that made these structures cohere are overcome by an even more powerful antigravity force. In addition, we'll never get the chance to watch galaxies evolve beyond a certain stage because the objects will disappear from view before the cycle is complete. Cosmic acceleration also will limit opportunities for extragalactic communications, with some distant galaxies already out of range. "That's a blow to the SETI community, but maybe there's nothing out there," says Loeb.

When the universe is ten times older, we won't be able to see anything beyond our own megagalaxy, and extragalactic astronomy will cease to exist. When we can no longer peer into the distant past, observational cosmology also will come to an end. Light that has been traveling since shortly after the Big Bang, the microwave background radiation, won't completely disappear, but it will become so distended by cosmic expansion that the wavelength of these photons will exceed the length of the observable universe, making them undetectable. "If any astronomers are living 100 billion years from now, they could have a pretty boring life," Evrard says.

Adams doesn't care what astronomers might or might not be doing at that time. "I don't have anything to say about what humans might be up to in a billion years," he notes. "But if you ask me what a star will be doing in a billion years, I have plenty to say." A more sensible focus, for him, is to look at what will happen to the astrophysical objects that populate our universe as the cosmos is ripped apart by acceleration.

Once other galaxies recede from view, astronomers will be limited to studying objects within our own little piece of heaven. Galactic astronomy, in other words, will be the only game in town. Although our Sun, a medium-mass star, will be around for just another 5 billion years or so, the lowest mass stars are expected to burn hydrogen for 10 to 20 trillion years. New stars will continue to form; but with less material available, most of these stars will burn out within 100 trillion years. At that point, the only way to make new stars will be through collisions among brown dwarfs. Because these crashes occur infrequently, one might expect only a few stars to shine in each galaxy.

Stars are occasionally hurled from galaxies, so statistically, if we wait long enough (Adams predicts 10^{20} years), galaxies themselves will cease to exist. No longer bound to galaxies, dead stars will be



scattered far and wide. Each object will lead a lonely existence until it eventually disintegrates due to proton decay, although the lifetime of protons is so long it has yet to be determined experimentally.

The last remaining astronomical objects, black holes, will ultimately "evaporate" due to Hawking radiation. For the biggest black holes, this process is expected to take 10^{100} years. Apart from photons stretched to ungodly dimensions and some stray particles — electrons, protons, and neutrinos — everything else will be gone. "There'll be nothing left to measure and no one left to measure it," says Banks.

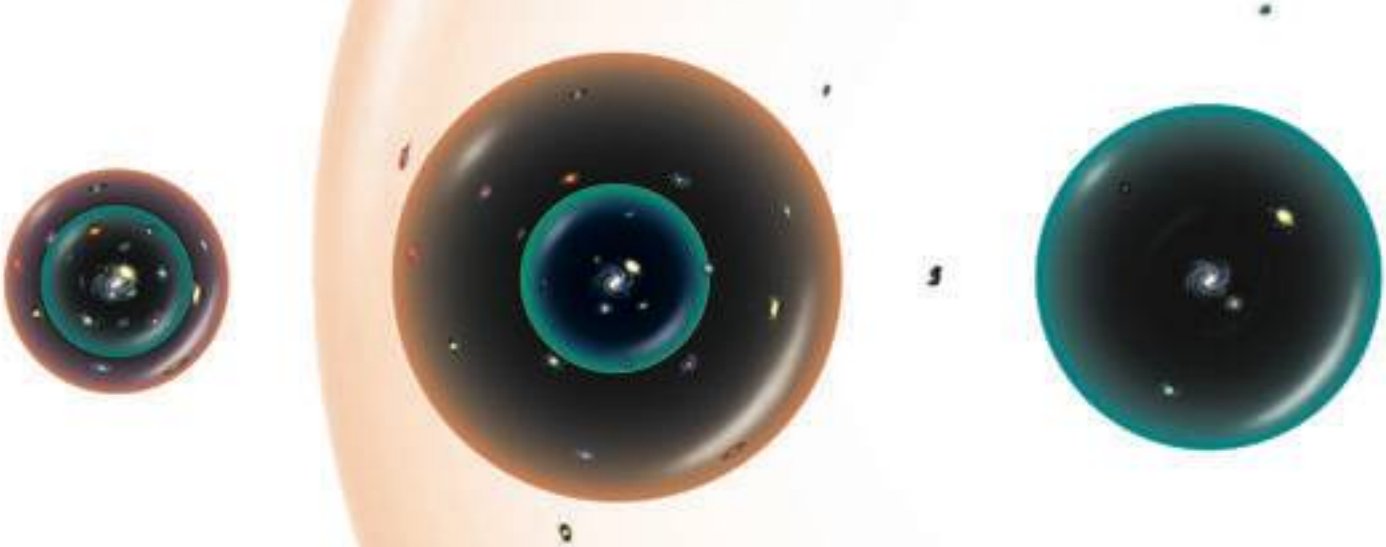
Caveats, of course, apply to all speculation about the distant future: The farther in time we go, the greater the uncertainty. "Any forecasts we make are predicated on the laws of physics remaining unchanged," says Adams. "You can't do anything without that article of faith. But once you know the laws of physics, assuming they don't change, you can go pretty far."

One hundred billion years is, admittedly, a long time, but it's no longer than the projected life span of the longest-lived main sequence stars. And, as Loeb points out, a factor of ten increase is not a big deal for physicists who routinely manipulate far bigger numbers. University of Pennsylvania cosmologist Max Tegmark agrees that a tenfold extrapolation "does not take a wild leap of faith. But that doesn't mean the expansion will continue forever. Eventually, dark energy may decay, causing the universe to contract again."

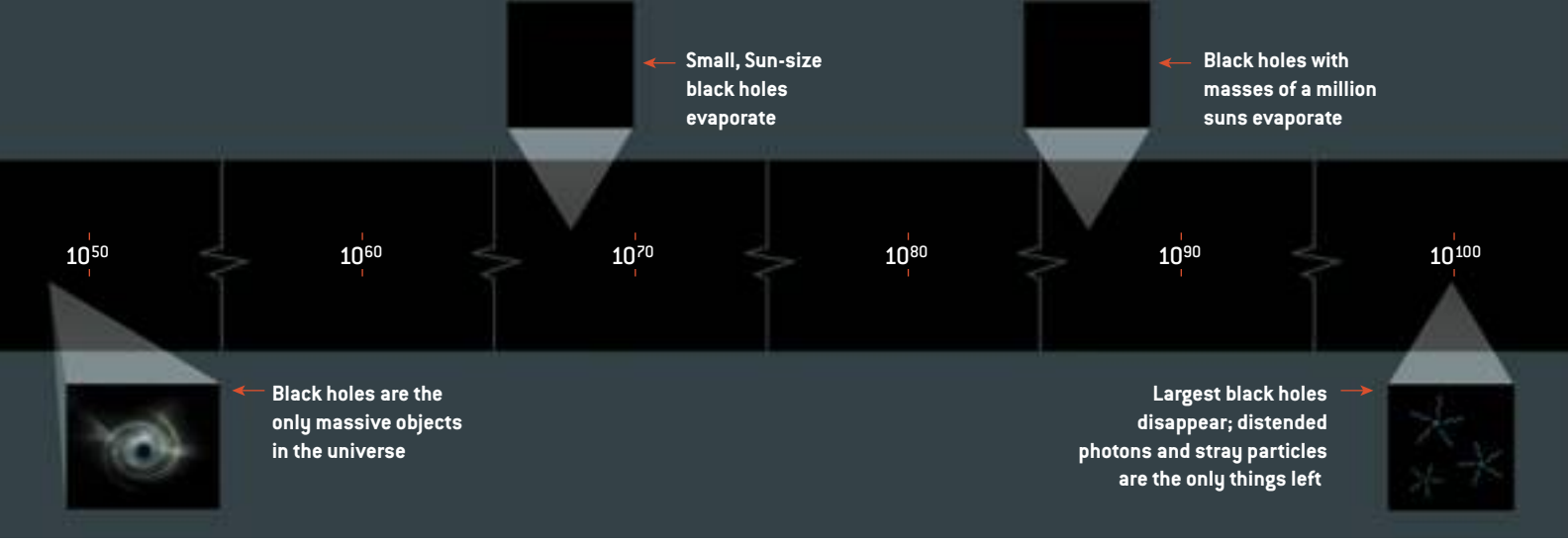
The obvious lesson is that we can't predict the future with confidence until we know what dark energy really is. The calculations of Adams, Evrard, and Loeb assume a cosmological constant, but if dark energy varies over time, the whole picture changes. In view of this fundamental uncertainty, all long-range forecasts must be considered tentative at best.

Saul Perlmutter, an astrophysicist at the Lawrence Berkeley National Laboratory and leader of one of two teams credited with discovering cosmic acceleration, believes that key parts of the story are still missing. To the standard inflationary universe model, he says, we've already added dark matter and dark energy. "If you add enough things like that, you have to wonder whether you really understand this picture," he says.

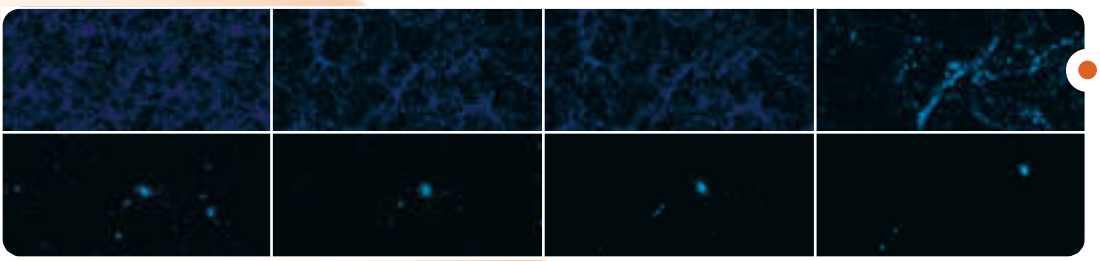
The cosmological constant, although still not understood, is the simplest explanation for cosmic acceleration. But alternatives such as quintessence — a hypothetical form of matter that eventually



DARK ENERGY will expand the universe, but not our horizons. Because light travels at a finite speed, only light from galaxies within a certain range has had time to get here. As space grows apart ever faster, the portion of the universe we can see (green spheres) will constitute a diminishing fraction of the whole (peach spheres represent an arbitrary region outside our purview). When the universe is about ten times its current age, we'll be able to see objects only within a 40-billion-light-year radius. *ASTRONOMY:* JAY SMITH


Small, Sun-size black holes evaporate
Black holes with masses of a million suns evaporate
10^{50}
10^{60}
10^{70}
10^{80}
10^{90}
10^{100}
Black holes are the only massive objects in the universe
Largest black holes disappear; distended photons and stray particles are the only things left

decays — have been proposed. "Quintessence doesn't arise as naturally in our theoretical models, yet many theorists are unhappy with the cosmological constant, as well," says Banks. The reason for their unrest stems from the fact that a cosmological constant dashes any hope of formulating a precise mathematical theory of the universe. "If you have enough time, you can measure things with absolute precision, but to do that, you need an open universe that grows slowly enough that you can, in principle, measure everything in the universe," he explains. Cosmic acceleration, however, makes that impossible because so much of the universe will become inaccessible. "We can still predict things with enough precision that any sane person would be satisfied," says Banks, "but it's annoying to those of us who seek absolute perfection."



THE ACCELERATING EXPANSION of space will stretch the cosmic web, upon which galaxies cluster, to the breaking point. Clockwise from upper left: Simulations show a slice of the universe at eight epochs (in billions of years after the Big Bang): 2.8, 6.5, 14, 24, 33, 44, 65, and 75. M. BUSHA, R. WECHSLER, F. ADAMS, G. EVRARD/MICH. ACADEMIC COMPUTING CENTER

Carpe diem

Ultimately, we may have to accept the notion of an accelerating universe propelled by a cosmological constant, the disappointment of theorists notwithstanding. "If the universe has a constant vacuum energy, it will expand exponentially, and there's no way to prevent it," says Loeb. "In the meantime, we should use our telescopes to get as much information as quickly as we can."

"We need to make the best of our brief moment in the Sun," agrees Krauss. The recent recognition of an accelerating universe won't call for a fundamental shift in astronomical priorities — a steady push to see farther and deeper into the sky — "but now there's an even greater urgency. This should inspire astronomers to make every day more useful."

The perspective provided by the futuristic calculations of Adams, Evrard, Loeb, Krauss, and others can help us appreciate that we live in what Tegmark calls "the golden age of astronomy." There were far fewer sources to see when the universe was a fraction of its current age, and fewer still will remain within view as the universe splits apart into isolated enclaves.

Yet upon contemplating where cosmic acceleration is taking us, some investigators find the prospects disheartening. A universe dominated by a cosmological constant is "the bleakest of all outcomes, offering no chance to do cosmology, no chance for rebirth — just a long, cold death," according to Brian Schmidt, an astronomer at the Australia National University who heads the second observational team credited with the discovery of dark energy. There's no long-term future in an accelerating universe, adds Krauss, as civilizations (along with life in any form) ultimately are doomed and knowledge destined to be forgotten.

Banks takes issue with such views, dismissing them as "the ultimate in hubris. We're a minor phenomenon in the cosmos and imagining that we could be here forever is silly," he says. "We're around for a brief time in the lifetime of the universe, and we should enjoy it while we can."

In looking ahead trillions of years from now, Adams doesn't consider the future dismal at all. On the contrary, he says, "I find it empowering that we can understand the laws of physics well enough to make statements about what will happen in a trillion years with some confidence."

Until cosmic acceleration gained acceptance, the previously favored scenario — an expanding universe that decelerates over time, slowly approaching a halt but never getting there — led to what Evrard considers a "boring" conclusion. "Now it seems we're headed to another, more dramatic end — a rocket ride," he says.

That's one way of describing our fate, but it might also be put in other, less appealing terms: a faster-than-expected trip to oblivion. To all you passengers out there, the "fasten seatbelt" lights are now flashing. Sit back, buckle up, and enjoy the ride.

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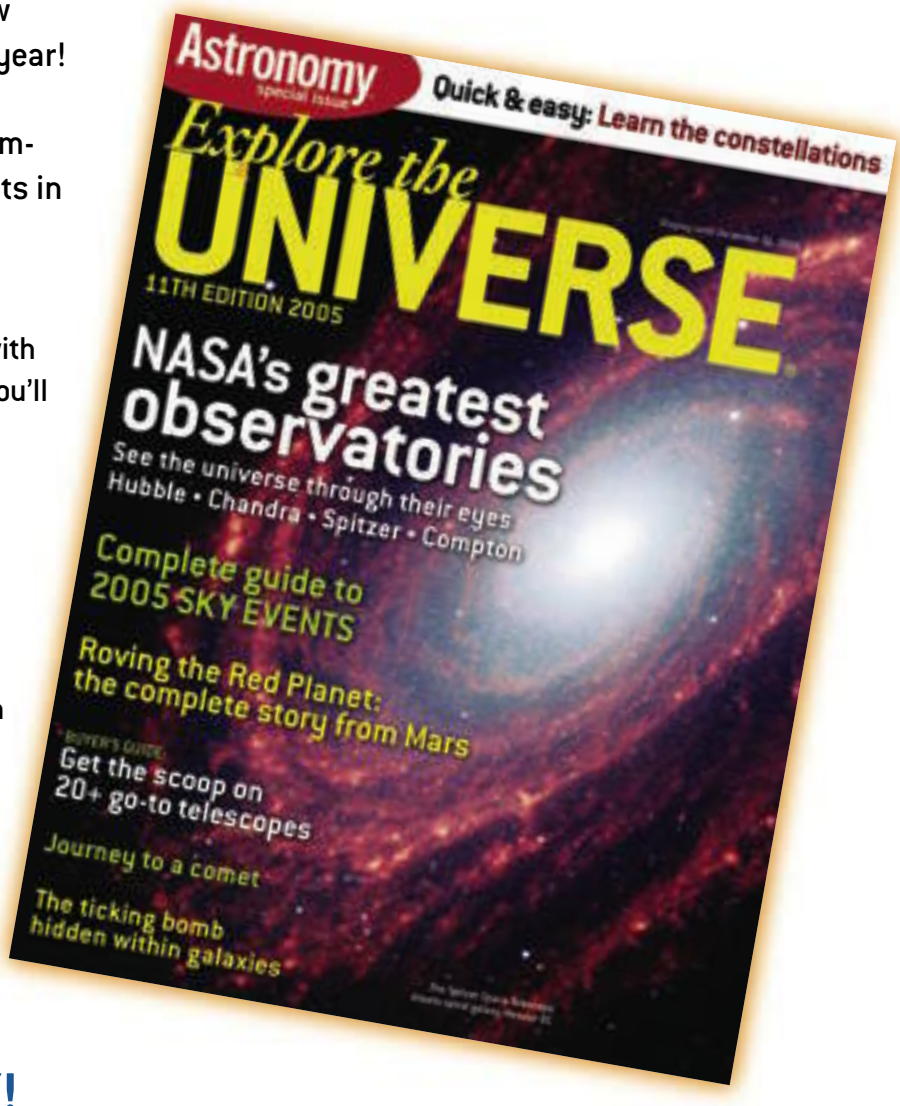
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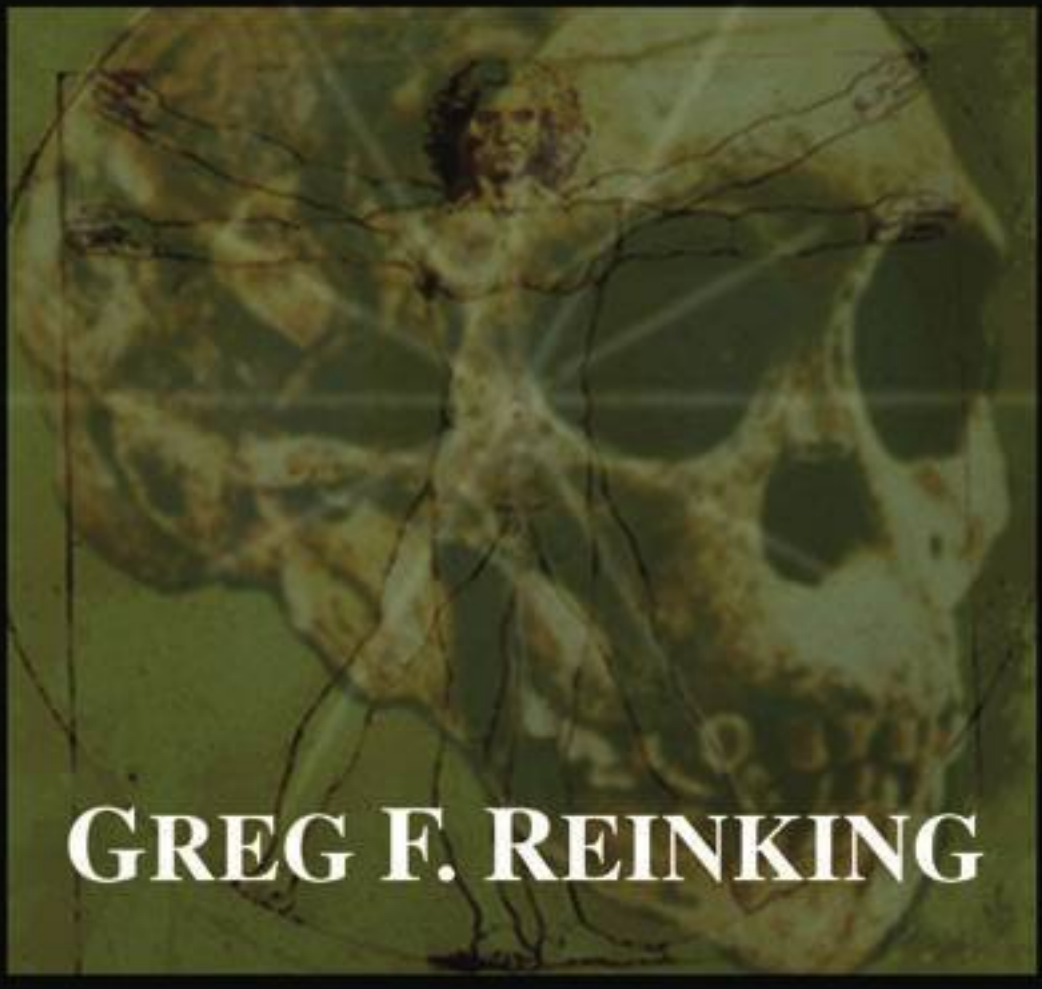

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